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**Color Fields:
What Designers Need to Know About Color**

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**Color Fields:
What Designers Need to Know About Color**

by

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Report

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Dedication

For Gabriel and Evelyn

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Abstract

Color Fields: What Designers Need to Know About Color

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The University of Texas at Austin, 2016

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The goal of this report is to identify what designers today need to know or understand about color and—consequently—what design educators should be teaching design students about color. While designers use color intuitively like artists, they also use color instrumentally as a means of communication and a medium for creation. Fine arts paint-mixing models of instruction have long dominated color education for designers. While traditional color education holds much value, I propose that today, designers need a more complete understanding, which includes color theory, color systems, color materials¹ and color management. Design educators, therefore, should teach more about the use of color in practice: color management, color science, and color systems (such as CIE, Pantone, NCS and Munsell) that are used today in design, commerce and industry.²

¹ “Color materials” include ink, paint, paper and light, as well as Plexiglas, vinyl, textiles, ceramics, etc.

² Nigel Cross, "Designerly Ways of Knowing: Design Discipline Versus Design Science" *Design Issues* 17, no. 3 (2001): 49–55.

I seek to help designers and educators achieve a more comprehensive understanding of color through a series of artifacts designed to illustrate color concepts and through a curated list of existing print and online color resources. These artifacts and resources provide methods for design educators to teach a more contemporary, comprehensive and practice-based understanding of color. The artifacts at the center of this project are didactic toys that demonstrate important concepts in color theory and form a system that illustrates the technical and practical aspects of color as well as an updated framework for understanding color and its production.

Keywords: color, color application, color education, color management, color theory, color toys, design, design education, design practice

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INTRODUCTION

Color is one of the most fascinating, complex and useful tools for designers. Contemporary technological innovations have radically changed the way designers use color, and the impacts of this change are far reaching. Design increasingly depends upon digital technology as creation has moved from the analog to the digital and from the drafting board and darkroom to the monitor and laser printer.³ As digital technologies have become the primary means of production, designers have an ever-greater need to understand digital color and color management.

A design-centered way of understanding color is ultimately a practice-based understanding. Color is more than light and pigment. It is a central element of design that is achieved, modified and understood through the interaction of light and many different materials. Color is simultaneously a natural phenomenon and a powerful medium for communication.

This report presents newly gathered survey data, explores how professional designers use color today, and also offers a theoretical and historical outline of concepts that pertain to the use of color in various fields of design practice (including graphic applications, product development and architectural materials). It provides an overview of how color works, how it is defined as an applied concept, strategic tool and design medium and reviews the ways in which color is organized in contemporary color spaces and commercialized color systems.

The central argument of this paper is that there is a need for designers to cultivate a comprehensive, design-centered understanding of color and that this is best achieved by updating color education in art and design programs to be more current and practical.

³ Richard Benson, *The Printed Picture*, ed. David Fankel (New York: The Museum of Modern Art, 2008).

Designers need the technical skills to achieve color consistency across platforms from printed materials and architectural forms to digital screens and new media, successfully navigating the obstacles that exist between design and production.

This inquiry seeks to identify gaps (and thus areas of opportunity) between contemporary designers' use of color and the information presented to students through design textbooks and design curricula. How might we analyze and reimagine the use of color in design practice? What is the range of color media and tools available to designers and how might they best be utilized in design practice? What is the value and measure of “good” color education for designers? How might color education be updated to reflect how designers are using color now and will use it in the future? What practice-based methods and tools are available to define and cultivate a designerly understanding of color?

In this thesis project, I have identified the various needs of designers regarding the use of color in practice through an Institutional Review Board (IRB) approved survey of professional designers and design students. I have also designed objects that enable design students to more easily understand established color principles and theories. Finally, I have curated a list of existing resources (both online and in print) that enable designers to learn about (and educators to teach) contemporary color concepts and practices that are not comprehensively addressed in most design textbooks.

This report clarifies the pragmatic role of color in design practice and explains why it is so critical that designers understand contemporary color concepts. In short, the contribution of this project is not only to show how important it is to update color education for designers, but also to help educators teach color more effectively by identifying color concepts that are not well represented in post-secondary design education and identifying existing resources that support more up-to-date instruction.

A BRIEF HISTORY OF COLOR

In the attempt to explain what color is and how it works, color theorists have developed contemporary frameworks to understand color.⁴ However, many of the basic color theories and principles that are currently taught to art and design students were codified in the seventeenth century. The invention of systems to formalize color relationships dates back to the Greek philosopher Aristotle (384-322 B.C.), who produced a method of understanding color that is relatable to some of the three-dimensional color models in use today.⁵ In 1666, English mathematician and scholar Sir Isaac Newton (1643-1727) conducted experiments with a prism, coining the term spectrum to describe color in terms of absolute hues and corresponding wavelengths of light.⁶ He proposed that light was made of particles and created a circular chart that displayed seven spectral colors, which is essentially the (red-orange-yellow-green-blue-violet) color wheel that is seen today.⁷ Soon after, Dutch physicist Christiaan Huygens (1629-1695) argued that light, the source of all color, is best understood as a wave, and it is true that depending upon the experiment, light sometimes behaves like a wave and sometimes as a particle.⁸ It was not until the twentieth century that quantum theorists like Albert Einstein (1879-1955) and Max Planck (1858-1947) reconciled the wave and particle models of light via the concept of photons, pulsating units of energy, which travel through space.⁹

⁴ Edith Anderson Feisner and Ronald Reed, *Color Studies*, 3rd ed. (New York: Fairchild Publications, Inc., 2013).

⁵ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley Interscience, John Wiley & Sons, Inc., 2001).

⁶ Ibid.

⁷ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

⁸ Bruce Fraser, Chris Murphy and Fred Bunting, *Real World Color Management: Industrial-Strength Production Techniques* (Berkeley: Peachpit Press: 2009).

⁹ Ibid.

Color in the Nineteenth Century

Color became a topic of impassioned debate in the nineteenth century, which was characterized by a theoretical divide between physicists and psychologists.¹⁰ Physicists objectively studied the measurable data of colored light while psychologists focused on the complex mechanisms of human perception.¹¹ Meanwhile, leaders of the emerging color industry also made meaningful contributions that bridged this gap. The collective work of these theorists contributed to the development of today's technical color models, which are used to accurately specify color for both science and industry.¹²

Organic chemist Michel-Eugène Chevreul (1786–1889) became the major color authority for the industrial arts in the latter half of the nineteenth century.¹³ As the director of the Manufacture Nationale des Gobelins in Paris, which produced textiles for French government buildings and official gifts, he researched dye chemistry and focused on problems of color management.¹⁴ Chevreul's theory of color harmony was explained in his influential 1839 treatise, *The Principles of Harmony and Contrast of Colors and Their Applications to the Arts*.¹⁵ His major contributions were the laws of *successive contrast*, the “afterimage” experienced from gazing at an object for a long period of time and *simultaneous contrast*, the optical impact of adjacent colors in which two colors appear more disparate when in close proximity.¹⁶

¹⁰ Sally Cochrane, "The Munsell Color System: A Scientific Compromise from the World of Art, Part A," *Studies in History and Philosophy of Science*, 47 (2014): 26–41.

¹¹ Ibid.

¹² János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: Wiley Interscience, John Wiley & Sons, Inc., 2007).

¹³ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge & London: MIT Press, 2012).

¹⁴ Ibid.

¹⁵ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge & London: MIT Press, 2012); and Helle Crenzien and Michael Juul Holm, eds., *Color in Art* (Humblebæk, Denmark: Louisiana Museum of Modern Art, 2010).

¹⁶ Helle Crenzien and Michael Juul Holm, eds., *Color in Art* (Humblebæk, Denmark: Louisiana Museum of Modern Art, 2010).

On the scientific side of the debate, English scientist Thomas Young (1773–1829) formalized the *trichromacy theory* in 1801, which hypothesized that red, green, and blue were the three “primary” colors of light.¹⁷ German scientist Hermann Ludwig Ferdinand von Helmholtz (1821-1894) and Scottish scientist James Clerk Maxwell (1831-1879) later expanded the theory into the *Young-Helmholtz theory*.¹⁸ Helmholtz made the difference between light mixing and pigmentary color widely known and after Chevreul became the prominent scientific expert in paint color in the 1850s and 1860s.¹⁹ Maxwell identified three sets of optical receptors sensitive to red, green and blue light, which were confirmed in the 1960s when three types of color-sensing cones were observed in the retina.²⁰ This approach is the basis of modern color measurement or colorimetry.

From a psychological perspective, German poet Johann Wolfgang von Goethe (1749–1832) raised fundamental philosophical questions with his *Theory of Colours* (1810) which promoted observation and the visual experience of color while critiquing Newton’s and other scientists’ reliance upon externally measurable phenomena.²¹ Goethe proposed that color exists in contrast to light and that spectral colors are generated through the interaction of light and dark.²² Tying color measurement to human perception made way for the

¹⁷ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley Interscience, John Wiley & Sons, Inc., 2001).

¹⁸ Ibid.

¹⁹ John Gage, *Color and Meaning: Art, Science, and Symbolism* (Berkeley and Los Angeles: University of California Press, 1999).

²⁰ Ibid.

²¹ Linda Holtzschue, *Understanding Color: An Introduction for Designers* (New York: John Wiley & Sons, 2012); and Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley Interscience, John Wiley & Sons, Inc., 2001).

²² Eddie Opara and John Cantwell, *Best Practices for Graphic Designers, Color Works: Right Ways of Applying Color in Branding, Wayfinding, Information Design, Digital Environments and Pretty Much Everywhere Else* (Beverly, MA: Rockport Publishers, 2014).

possibility of independent color variables for hue specification, an important concept for colorimetry and industrial color order systems.²³

German philosopher Arthur Schopenhauer (1788-1860) built upon Goethe's theory in his 1816 treatise *On Vision and Colors* suggesting that all colors could be defined in terms of three opponent pairs that could be mapped on x, y and z axes to create a "three-dimensional" color space.²⁴ German physiologist Karl Ewald Konstantin Hering (1834-1918) formalized this approach in 1878 as the *opponent theory* of color perception, suggesting three distinct opponent pairs that govern color vision—red–green, yellow–blue and light–dark.²⁵ This theory was confirmed in the 1950s when opponent colors and an achromatic light-dark signal were first observed.²⁶ These scientists and theorists, from diverse disciplines, formed the philosophies that are the basis of our contemporary understanding of color.

Color in the Twentieth Century

In the twentieth century, two independent ways of thinking about color developed, one that focused on color standards, color science and industry, and another, developed by artists and educators that relied upon interpretation of nineteenth-century color theories.

COLOR MEASUREMENT, COLOR MANAGEMENT AND THE COLOR INDUSTRY

CIE: Commission Internationale de l'Eclairage

In 1931, the Commission Internationale de l'Eclairage (International Commission on Illumination) defined international standards for measurement and specification of colors, the

²³ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley Interscience, John Wiley & Sons, Inc., 2001); and Schopenhauer, Arthur, Georg Stahl, and Philipp Otto Runge, *On Vision and Colors* (New York: Princeton Architectural Press, 2010).

²⁴ Ibid.

²⁵ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley Interscience, John Wiley & Sons, Inc., 2001).

²⁶ Ibid.

CIE System of Colorimetry and the Standard Observer for Colorimetry.²⁷ Colorimetry provides methods to measure color stimuli (red, green, and blue light) and specifies color with appearance attributes (like brightness, chroma, saturation and hue).²⁸ The CIE is a nonprofit professional organization that promotes worldwide cooperation and the exchange of information relating to the science and art of light, color, vision and image technology.²⁹ The CIE developed a standardized way to accurately describe and measure even the most subtle color differences for both light sources and object surfaces.³⁰ CIE standards are used today for most technical descriptions of color images by digital devices including computers, cell phones, cameras, scanners and printers.³¹

The CIE provides color matching equations and parameters for standard white light sources for color measurement. It also defined three primary colors of light, the monochromatic wavelengths of: 700.0 nm (red), 546.1 nm (green) and 435.8 nm (blue).³²

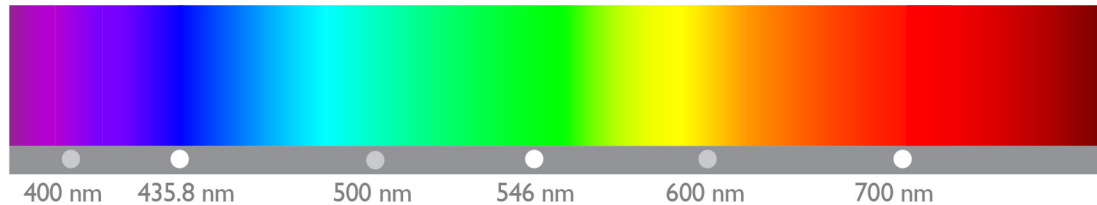


Figure 1: *Visible spectrum*³³

²⁷ János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: Wiley Interscience, John Wiley & Sons, Inc., 2007).

²⁸ Mark D. Fairchild, *Color Appearance Models* (West Sussex: John Wiley & Sons, 2013).

²⁹ CIE—International Commission on Illumination, "Advancing Knowledge and Providing Standardization to Improve the Lighted Environment," CIE 2016, accessed April 24, 2016, <http://www.cie.co.at/index.php/LEFTMENU/About+us>.

³⁰ Edith Anderson Feisner and Ronald Reed, *Color Studies, 3rd ed.* (New York: Fairchild Publications, Inc., 2013); and Yoshi Ohno, "Spectral Color Measurement," in *Colorimetry: Understanding the CIE System*, ed. János Schanda (Hoboken, NJ: John Wiley & Sons, 2007), 101–134.

³¹ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

³² Peter Bodrogi, trans. "Translation of CIE 1931 Resolutions on Colorimetry," in *Colorimetry: Understanding the CIE System* (Hoboken, NJ: Wiley Interscience, John Wiley & Sons, Inc., 2007), 1–23.

These spectral primaries or *tristimulus values* are mapped in three dimensions using a Cartesian coordinate system (XYZ coordinates) that are mixed at the ratio of 1:4.5907:0.0601 to produce white light.³⁴ In 1931 the CIE organized the range of tristimulus values into the CIE XYZ color space, which attempts to map every color that can be perceived by a typical human observer.³⁵

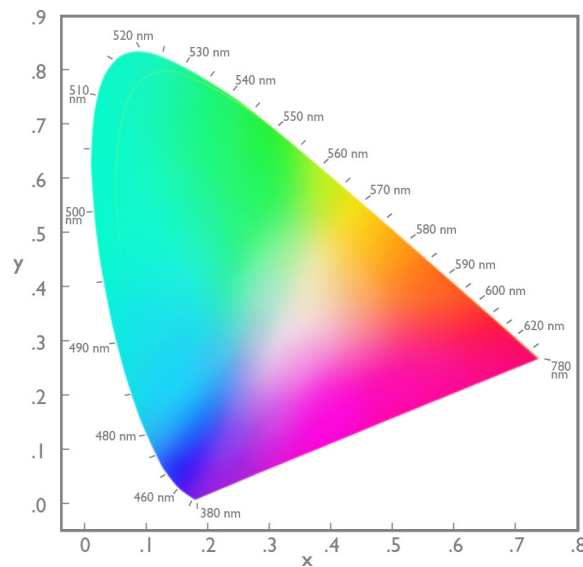


Figure 2: *CIE xy chromaticity diagram*³⁶

³³ Image adapted by author from Academo, "Wavelength to Colour Relationship," *Academo.org*, accessed April 24, 2016, <https://academo.org/demos/wavelength-to-colour-relationship>; and Public Domain, *Linear Visible Spectrum*, Wikimedia Creative Commons, August 27, 2008, accessed April 30, 2016, https://commons.wikimedia.org/wiki/File:Linear_visible_spectrum.svg.

³⁴ Peter Bodrogi, trans. "Translation of CIE 1931 Resolutions on Colorimetry," in *Colorimetry: Understanding the CIE System* (Hoboken, NJ: Wiley Interscience, John Wiley & Sons, Inc., 2007), 1–23; and Hugh S. Fairman, Michael H. Brill, and Henry Hemmendinger, "How the CIE 1931 Color-Matching Functions were Derived from Wright-Guild Data," *Color Research & Application* 22, no. 1 (1997): 11–23.

³⁵ Marko Tkaličič and Jurij F. Tasič, "Colour Spaces: Perceptual, Historical and Applicational Background," *The IEEE Region 8 EUROCON 2003* (2003): 304–308.

³⁶ Image adapted by author from Academo, "Wavelength to Colour Relationship," *Academo.org*, accessed April 24, 2016, <https://academo.org/demos/wavelength-to-colour-relationship>; János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: John Wiley & Sons, 2007: 9), and Public Domain, *CIE xy Chromaticity Diagram*, Wikimedia Creative Commons (2005), accessed June 10, 2016, <https://commons.wikimedia.org/wiki/File:CIExy1931.png>.

The CIE provides three ways to specify color: 1) the XYZ tristimulus values, 2) dominant wavelength λ nm and purity p , and 3) chromaticity coordinates x , y , Y (luminance).³⁷ The CIE xy chromaticity diagram (figure 2) provides a convenient two-dimensional representation of the range of visible colors. The third dimension (Y) is not shown in the diagram (and ranges perpendicularly from white to black).³⁸ Because this diagram attempts to represent a three-dimensional phenomenon with only two variables it is not used to accurately define specific colors or color spaces.³⁹

Color as a Profession

The first professional colorists in the United States included H. Ledyard Towle (1890–1973) and Arthur S. Allen (1900–1940). These strategists served as liaisons for consumers and the chemical color industry and introduced the design practices of color forecasting and visual streamlining.⁴⁰ U.S. industry leaders recognized color as well suited for mass production and embraced it as an essential design tool.⁴¹ Color forecasts became part of standard business practices, making way for increased efficiency and accuracy in color production, which ultimately resulted in new consumer expectations for color consistency in both print and everyday products.⁴²

The multi-million dollar color forecasting industry predicts and develops color trends for advertising and industry and is led by organizations like the Color Marketing Group (CMG), the Pantone Color Institute and the Color Association of

³⁷ Alan Parkin, *Digital Imaging Primer* (Heidelberg & Berlin: Springer, 2016).

³⁸ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

³⁹ Mark D. Fairchild, *Color Appearance Models* (West Sussex: John Wiley & Sons, 2013).

⁴⁰ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge and London: MIT Press, 2012).

⁴¹ Ibid.

⁴² Ibid.

the United States (CAUS).⁴³ Color palettes are developed through consensus by members and released as swatch books, the best known being Pantone.⁴⁴ These are the standardized colors we see across brands and manufacturers in products like home furnishings, fashion and cosmetics.

Color Safety Code

Faber Birren (1900–1988) was an author and expert in color psychology.⁴⁵ His 1937 book *Functional Color* investigated how business could use color to increase worker morale and productivity.⁴⁶ Functional color is based on an efficiency-centered industrial arts tradition that merged color design and human psychology to create a more efficient, enjoyable environment.⁴⁷ Birren developed the *DuPont Safety Color Code* (figure 3) for industry and when the U.S. Army later adopted the code it was subsequently reported that accidents were reduced from 46 to five per one thousand workers.⁴⁸

The code was so successful that it was made a national standard by the American National Standards Institute (ANSI) in 1945.⁴⁹ In 1978, Safety Color Code tolerance charts were formulated to include Munsell notations and CIE specifications (x, y, Y) for

⁴³ Linda Holtzschue, *Understanding Color: An Introduction for Designers* (New York: John Wiley & Sons, 2012); and Nancy Kuhl, “Origins of the Color Forecasting Industry,” *Yale University Beinecke Rare Book & Manuscript Library*, March 10, 2014, accessed February 6, 2016, <http://beinecke.library.yale.edu/about/blogs/room-26-cabinet-curiosities/2014/03/10/origins-color-forecasting-industry>.

⁴⁴ American National Standards Institute, *American National Standard Safety Color Code for Marking Physical Hazards and the Identification of Certain Equipment* (New York: American National Standards Institute, Inc., 1979), accessed May 25, 2016, http://triodyne.com/cribs/ansi_z53_1_1979.pdf; and Nancy Kuhl, “Origins of the Color Forecasting Industry,” *Yale University Beinecke Rare Book & Manuscript Library*, March 10, 2014, accessed February 6, 2016, <http://beinecke.library.yale.edu/about/blogs/room-26-cabinet-curiosities/2014/03/10/origins-color-forecasting-industry>.

⁴⁵ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge and London: MIT Press, 2012).

⁴⁶ Ibid.

⁴⁷ Faber Birren, “Functional Use of Color” in *Field Applied Paints and Coatings* (Washington, D.C., Building Research Institute, 1959): 93–95; and Regina Lee Blaszczyk, *The Color Revolution* (Cambridge and London: MIT Press, 2012).

⁴⁸ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge and London: MIT Press, 2012).

⁴⁹ Ibid.

each standard color.⁵⁰ The ANSI Z535 Safety Color Chart provides color samples, ink formulations and PANTONE® colors.⁵¹ Specifications for these colors can be purchased from the ANSI website.



Figure 3: *Safety code colors*⁵²

FOUNDATIONS OF COLOR IN DESIGN EDUCATION, ART AND ARCHITECTURE

In the early to mid-twentieth century, a number of prominent architects, designers and artists promoted color concepts that were influential for designers and design educators. I have focused on theories that contextualize color as a central design element and demonstrate the power of color as a tool to impact design outcomes. These artistic theories are the origin of the color approaches we see applied in design and architecture practices today.

The Bauhaus school in Weimar, Germany, made influential contributions to color instruction especially through the work of Johannes Itten (1888–1967) and Joseph Albers (Joseph Albers 1888–1976).⁵³ Itten's nearly century-old pigment-

⁵⁰ American National Standards Institute, *American National Standard Safety Color Code for Marking Physical Hazards and the Identification of Certain Equipment* (New York: American National Standards Institute, Inc., 1979), accessed May 25, 2016, http://triodyne.com/cribs/ansi_z53_1_1979.pdf.

⁵¹ American National Standards Institute, *American National Standard Environmental and Facility Safety Signs* (New York: American National Standards Institute, Inc., 2011).

⁵² Image by author, information from Regina Lee Blaszczyk, *The Color Revolution* (Cambridge and London: MIT Press, 2012); and Casey Hayes, "Know the Codes," *Industrial Safety & Hygiene News* 39, no. 9 (2005): 53.

⁵³ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

based theories, color harmony charts and iconic version of the RYB color wheel still serve as the foundation of basic color training for designers and painters today.⁵⁴ His books *The Art of Color* (1964) and *The Elements of Color* (1970) are commonly assigned in foundational color courses. Joseph Albers, Itten's colleague at the Bauhaus and professor at Yale University, rejected the formality of color-order systems such as Munsell's (see page 52) in favor of eye-training exercises designed to help students gain an advanced visual understanding of the relativity and variability of color.⁵⁵ This approach was outlined in his 1963 book *The Interaction of Color*, which is a seminal color text for designers and artists.

Color and Art

Art has historically played a vital role in designers' understanding of color. Visual artists, often painters, developed innovative ways of conceptualizing and using color that have been coopted by both designers and architects. A short list of influential painters that were considered colorists include Delacroix, Monet, Matisse, Seurat, van Gogh, Klee, Cézanne, Mondrian and Degas.⁵⁶ Color plays a communicative, almost visceral role as a central element of their work. Many of these artists looked to science for a deeper understanding of color. Eugène Delacroix, a French colorist and painter, was influenced by the work of Michel-Eugène Chevreul (the Parisian chemist) and experimented with the optical phenomenon of simultaneous contrast in his paintings.⁵⁷ Chevreul's innovations also inspired the

⁵⁴ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

⁵⁵ Josef Albers, *Interaction of Color* (New Haven & London: Yale University Press, 1963); and Linda Holtzschue, *Understanding Color: An Introduction for Designers* (New York: John Wiley & Sons, 2012).

⁵⁶ John Gage, *Color and Culture: Practice and Meaning from Antiquity to Abstraction* (London: Thames and Hudson, 2012).

⁵⁷ Ibid.

Impressionists (1874–1886) like Monet, Cassatt, Degas and Renoir, who interpreted new scientific discoveries and developed innovative ways to accurately render the nuances of color and light.⁵⁸ The science of optical effects, likewise, became a primary emphasis for the Neo-Impressionists (1886–1891) including Matisse, Seurat and Pissarro.⁵⁹ Georges Seurat translated basic concepts of color science, including optical mixing; to create a new style of painting called pointillism. Seurat adapted ideas about pigment, the physics of light and the psychology of color perception from Rood’s *Modern Chromatics* (1879) and Chevreul’s *Principles of Harmony and Contrast of Colors* (1855).⁶⁰

Both the Impressionists and the Neo-Impressionists focused on the problems of color and approached them in new ways. For example, in the late 1940s, Matisse innovated the concept of color as medium through a series of paper cutouts. He said, “Cutting directly into color reminds me of a sculptor’s carving into stone.”⁶¹ The forms and colors of the cutouts were architecturally applied in the design for the stained glass windows of the *Chapelle du Rosaire de Vence* (figure 4). Matisse intended to demonstrate the interaction of color (simultaneous contrast) with this groundbreaking design.⁶²

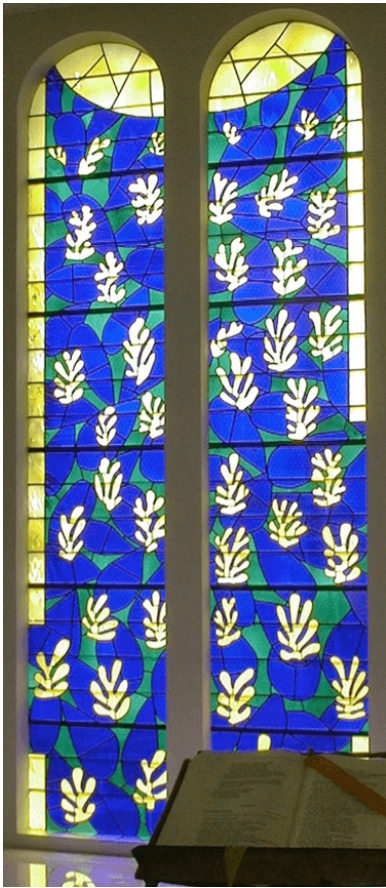
⁵⁸ Russell T. Clement and Annick Houzé, *Neo-Impressionist Painters: A Sourcebook on Georges Seurat, Camille Pissarro, Paul Signac, Théo Van Rysselberghe, Henri Edmond Cross, Charles Angrand, Maximilien Luce, and Albert Dubois-Pillet* (Westport, CT: Greenwood Press, 1999); and Edith Anderson Feisner and Ronald Reed, *Color Studies*, 3rd ed. (New York: Fairchild Publications, Inc., 2013).

⁵⁹ John Gage, *Color and Culture: Practice and Meaning from Antiquity to Abstraction* (London: Thames and Hudson, 2012); and Edith Anderson Feisner and Ronald Reed, *Color Studies*, 3rd ed. (New York: Fairchild Publications, Inc., 2013).

⁶⁰ John Gage, *Color and Culture: Practice and Meaning from Antiquity to Abstraction* (London: Thames and Hudson, 2012); and John Gage, *Color and Meaning: Art, Science, and Symbolism* (Berkeley & Los Angeles: University of California Press, 1999).

⁶¹ Charles A. Riley, *Color Codes: Modern Theories of Color in Philosophy, Painting and Architecture, Literature, Music, and Psychology* (Hanover & London: University Press of New England, 1995): 138.

⁶² Helle Crenzien and Michael Juul Holm, eds., *Color in Art* (Humblebæk, Denmark: Louisiana Museum of Modern Art, 2010).



*I have tried to achieve that balance of forces; the blues, greens and yellows of the windows compose a light within the chapel, which is not strictly any of the colors used, but the living product of their mutual blending.*⁶³

Henri Matisse innovated the prelude to Color Field Painting (1950–1975), its hallmark being vast expanses of vibrant color.⁶⁴ In these paintings color is the central focus, and color relationships take precedence.⁶⁵ Color field painters, including Ellsworth Kelly, Helen Frankenthaler, Mark Rothko, and Frank Stella, explored structure and metaphor through minimalism, form, space and color.⁶⁶

Figure 4: Henri Matisse. *Chapelle de Rosaire du Vence*, 1951. Vence, France. (Photo courtesy of Monica Arellano-Ongpin, *Flickr Creative Commons*, 2012.)

Kelly's work specifically emphasized form, color and spatial unity.⁶⁷ He was well versed in color theory and trained in Munsell's color system at the Pratt Institute in Brooklyn in the 1940s.⁶⁸

⁶³ Charles A. Riley, *Color Codes: Modern Theories of Color in Philosophy, Painting and Architecture, Literature, Music, and Psychology* (Hanover & London: University Press of New England, 1995): 141.

⁶⁴ Ann Temkin, *Color Chart: Reinventing Color, 1950 to Today* (New York: The Museum of Modern Art, 2008); and Karen Wilkin and Carl Belz, *Color as Field: American Painting, 1950–1975* (New Haven & London: Yale University Press, 2007).

⁶⁵ Ibid.

⁶⁶ Ann Temkin, *Color Chart: Reinventing Color, 1950 to Today* (New York: The Museum of Modern Art, 2008); Karen Wilkin and Carl Belz, *Color as Field: American Painting, 1950–1975* (New Haven & London: Yale University Press, 2007); and James Turrell et al., *James Turrell: A Retrospective* (Los Angeles: Los Angeles County Museum of Art, 2013).

⁶⁷ Fred S. Kleiner, *Gardner's Art through the Ages: The Western Perspective, Vol. I* (Boston: Cengage Learning, 2016).

⁶⁸ Ann Temkin, *Color Chart: Reinventing Color, 1950 to Today* (New York: The Museum of Modern Art, 2008).



Figure 5: Ellsworth Kelly. *Color Panels (Red, Yellow, Blue, Green, Purple)*. Frank Gehry, *Fondation Louis Vuitton Museum*. Paris, France. (Photo courtesy © Ellsworth Kelly © Fondation Louis Vuitton photograph by Marc Domage, *Flickr Creative Commons*, 2014.)

Color and Architecture: Defining Space

Founded in 1917 by painters Piet Mondrian and Theo van Doesburg, the Dutch De Stijl movement explored a similar use of color through standardized, prefabricated components for architectural spaces.⁶⁹ Architects like Gerrit Rietveld and J.J.P. Oud transferred De Stijl principles from painting to furniture design and architecture.⁷⁰ De Stijl architecture conceptually placed color and materials on equal footing, conceiving of color as a tangible building material, a concept that is echoed in the application of color in modern and contemporary architecture.⁷¹

⁶⁹ Helle Crenzien and Michael Juul Holm, eds., *Color in Art* (Humlebak, Denmark: Louisiana Museum of Modern Art, 2010).

⁷⁰ Stephen Sennott, *Encyclopedia of Twentieth Century Architecture, Vol. 3*. (New York & London: Fitzroy Dearborn, Taylor & Francis, 2004).

⁷¹ Helle Crenzien and Michael Juul Holm, eds., *Color in Art* (Humlebak, Denmark: Louisiana Museum of Modern Art, 2010).

There is a prevalent misunderstanding that modern architecture was largely monochromatic in style, but modernist interiors were much more colorful than historic photographs suggest.⁷² A 2010 *New York Times* editorial points out that many people are unaware of the prevalence of integral colors found at iconic modernist sites like the Bauhaus buildings at Dessau (1925–1926) designed by Walter Gropius (1883–1969) and Villa Savoye (1929–1930) by Le Corbusier (1887–1965).⁷³ As authors Tom Fraser and Adam Banks wrote, “Architects working in the modernist tradition did not want to outlaw color, just to see it used sympathetically.”⁷⁴

Le Corbusier (Charles-Édouard Jeanneret), pioneer of modern architecture, was known for both stark white interiors and innovative use of color.⁷⁵ In 1930 and 1931 Le Corbusier identified a series of 43 color tones that he relied upon to influence spatial relationships in his buildings.⁷⁶ A Swiss company, KT Color, manufactures 80 shades of paint in the Le Corbusier collection.⁷⁷ Journalist Alice Rawsthorn believes that these colors have enduring value because the architect chose them to work well with two particular styles—the classic white walls of his early interiors and the raw concrete and wood of his later work—both of which have endured in contemporary architecture and interior design.⁷⁸

⁷² Kim Beil, "The Myth of Black and White Modernism: Color Photographs and the Politics of Retrojective Looking," *Visual Resources* 31, no. 3-4 (2015): 127–153; and Alice Rawsthorn, "His True Colors," *T: The New York Times Style Magazine*, September 28, 2010, accessed March 15, 2016, <http://tmagazine.blogs.nytimes.com/2010/09/28/his-true-colors>.

⁷³ Kim Beil, "The Myth of Black and White Modernism: Color Photographs and the Politics of Retrojective Looking," *Visual Resources* 31, no. 3-4 (2015): 127–153.

⁷⁴ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004): 76.

⁷⁵ Alice Rawsthorn, "His True Colors," *T: The New York Times Style Magazine*, September 28, 2010, accessed March 15, 2016, <http://tmagazine.blogs.nytimes.com/2010/09/28/his-true-colors>.

⁷⁶ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

⁷⁷ Alice Rawsthorn, "His True Colors," *T: The New York Times Style Magazine*, September 28, 2010, accessed March 15, 2016, <http://tmagazine.blogs.nytimes.com/2010/09/28/his-true-colors>.

⁷⁸ *Ibid.*

The 1963 Centre Le Corbusier, La Maison de L'Homme was the architect's final building and incorporated color transparency and strong color contrasts.⁷⁹ The building is constructed of modular cubes each comprising an area of 266 inches square, made of enameled metal painted red, green, black, yellow and white.⁸⁰



Figure 6: Le Corbusier. *Centre Le Corbusier (Heidi Weber Museum)*, 1963. Zürich-Seefeld, Switzerland. (Photo courtesy of Roland Fischer, *Wikimedia Commons*, 2011.)

French-born, Tokyo-based architect Emmanuelle Moureaux employs color as a tool to evoke depth, pattern and emotion, and often uses flat planes of vibrant color.⁸¹ The first task she completes when beginning a project is deciding how many colors she will use.⁸² Moureaux says, "I create spaces through colors. I use colors as three-dimensional elements, like layers, in order to create spaces, not as a finishing touch

⁷⁹ Helle Crenzien and Michael Juul Holm, eds., *Color in Art* (Humblebæk, Denmark: Louisiana Museum of Modern Art, 2010).

⁸⁰ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

⁸¹ Winifred Bird, "French Architect Brings Brilliant Color to Tokyo," *Dwell*, August 19, 2014, accessed June 15, 2016, <http://www.dwell.com/modern-world/article/french-architect-brings-brilliant-color-tokyo>.

⁸² *Ibid.*

applied to surfaces. Color is not only beautiful. Color is structural and color is powerful.”⁸³ She also said, “...I think color must play an essential role in architecture: structuring the space itself.”⁸⁴



Figure 7: Emmanuelle Moureaux. *Sugamo Shinkin Bank*, 2010. Tokyo, Japan. (Photo courtesy of Forgemind ArchiMedia, *Flickr Creative Commons*, 2010.)

An advanced understanding of color, as illustrated by the examples in the previous section, is often the result of a synthesis of formal education, individual research, personal interest and professional practice. As I will outline in the next section, designers and artists alike see color as vitally important to design as a discipline. If color is such a central, important component of design, how then can we bring it to the center of design education?

⁸³ Gingko Press, *Color and Space in Architecture and Interior Design: Commercial, Corporate, Dining, Educational, Public, Residential, Recreational* (Berkeley: Gingko Press, 2013), 5.

⁸⁴ Gingko Press, *Color and Space in Architecture and Interior Design: Commercial, Corporate, Dining, Educational, Public, Residential, Recreational* (Berkeley: Gingko Press, 2013), 4.

COLOR IN DESIGN EDUCATION

How are the intricacies of color studied and imparted in post-secondary design education? Generally, color is taught to design students through introductory design courses (that teach basic color principles), color-specific design courses and online tutorials. Students also learn about color in classes related to design such as art history, drawing, painting and graphic communications courses, but technical color knowledge from these areas is rarely meaningfully integrated. It is time that color education is updated to include a contemporary understanding of both color theory and the use of color in design practice.

Beginning in March of 2016, I collected data from 88 design professionals and students through an IRB-approved survey.⁸⁵ The survey reveals that most designers learned about the technical aspects of color outside of formal education through individual research, internships and job experience.⁸⁶ Even upper-level design students may struggle to explain the difference between the CMYK and RGB color models, much less have a confident command of color both aesthetically and pragmatically. Only incidentally do students learn about color management, the use of color in marketing and branding or how to use color systems like Pantone. Therefore, design education is failing to teach students adequate practical and technical color skills. As the authors of one design textbook aptly observed, “Color is a language that we desperately need to master, but we need easier methods for it to become more relevant to today’s designer’s needs.”⁸⁷

⁸⁵ The University of Texas at Austin Institutional Review Board (IRB) ensures that research conducted on campus complies with all applicable laws, regulations and University policies.

⁸⁶ Diana Witcher, *What Designers Need to Know About Color* (Survey #2015-09-0131, May 2016).

⁸⁷ Eddie Opara and John Cantwell, *Best Practices for Graphic Designers, Color Works: Right Ways of Applying Color in Branding, Wayfinding, Information Design, Digital Environments and Pretty Much Everywhere Else* (Beverly, MA: Rockport Publishers, 2014).

Color textbooks for designers generally present a patchwork of information about color history, color systems, color psychology and the use of color in design. Many are overly simplified or difficult to read and do not include much-needed information about the technical aspects of color production. The following are among the best of the existing textbooks for designers and have made valuable contributions to the topic: *Color Studies* (2013) by Edith Anderson Feisner and Ronald Reed, *Understanding Color: an Introduction for Designers* (2012) by Linda Holtzschue, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (2004) by Tom Fraser and Adam Banks, and *Best Practices for Graphic Designers, Color Works: Right Ways of Applying Color in Branding, Wayfinding, Information Design, Digital Environments and Pretty Much Everywhere Else* (2014) by Eddie Opara and John Cantwell. *Interaction of Color* (1963) by Josef Albers and Johannes Itten's *The Elements of Color* (1970) are fundamental reading material for those interested in color. Regina Lee Blaszczyk provides a fascinating look into color, fashion and industry in the *The Color Revolution* (2012).

Color Research and Application journal (published by John Wiley & Sons and endorsed by the Inter-Society Color Council) provides a range of current articles about color including science, technology and the application of color in design, art, business, education and industry.⁸⁸ There are also a number of excellent, comprehensive, technically-oriented books about color written for color professionals and color scientists, the most useful for this review include *The Physics and Chemistry of Color* (2001), by Kurt Nassau, *Colorimetry: Understanding the CIE System* (2007), edited by János Schanda, *Color Appearance Models* by Mark D. Fairchild (2013), *Color Management & Quality Output: Working with Color from Camera to Display to Print* (2014) by Tom P. Ashe,

⁸⁸ Inter-Society Color Council, "Inter-Society Color Council: Where Art, Science and Industry Meet," *Inter-Society Color Council*, 2015, accessed May 15, 2016, <http://www.iscc.org/pdf/Brochure2015.pdf>.

and Bruce Fraser, et al.'s *Real World Color Management* (2004). Although these are perhaps too technical and complex for the needs of most design students, unquestionably, some of the technical information outlined in these books should be integrated into color textbooks targeted to design students.

In short, though specialist publications that explain the technical details of contemporary color theory and use for both printing and digital media are readily available, little of this knowledge is communicated to design students through curricula or standard textbooks. This makes it more difficult for students to learn about the current industry standards and best practices for color management they will need to know after graduation. Furthermore, it would be useful for designers to formally define the function, meaning and best practices for color in the field of design. The following section looks at what designers have to say.

Thesis Research: Survey and Artifacts

SURVEY

In order to determine what contemporary design professionals need to know about color, I conducted a survey of designers, design educators and upper level design students between March 5th and May 5th of 2016. After receiving approval from the University of Texas at Austin Institutional Review Board (IRB), I sent a anonymous link to a survey titled “What Designers Need to Know About Color” to designers and educators I know professionally and asked them to send it to designers and educators who have an interest or specialty in color. The 88 respondents included design students, graphic designers, industrial designers, interaction designers, interior designers and architects. Educators comprised 32% of the respondents and students comprised 48%.⁸⁹ The remaining participants were

⁸⁹ Diana Witcher, *What Designers Need to Know About Color* (Survey #2015-09-0131, May 2016).

professional designers, and there was considerable overlap between these three categories. Respondents were allowed to choose more than one professional category, for example, many graduate students are professional designers, educators and students.

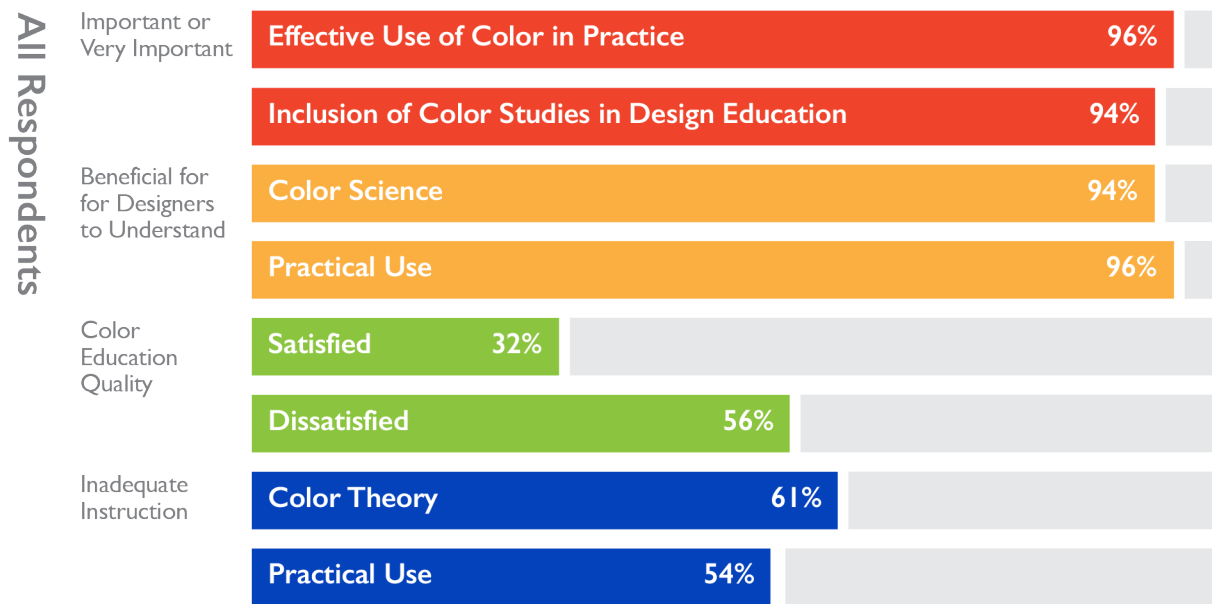


Figure 8: *Survey of all respondents*⁹⁰

Most respondents rated both the effective use of color in design practice (96%) and the inclusion of color in design education (94%) as important or very important. Most respondents felt that designers could benefit from an advanced understanding of color science (94%) and an increased understanding of the practical and technical use of color (96%). A slight majority (56%) of respondents were dissatisfied (or somewhat dissatisfied) with the quality of color education at the last educational institution they attended with 32% being satisfied or very satisfied. Most respondents said that design

⁹⁰ Data from *What Designers Need to Know About Color* (Survey #2015-09-0131, 2016).

students generally do not receive adequate instruction in either color theory (61%) or the practical and technical use of color (54%).⁹¹

A majority of educators (55%) reported that, of the content they teach, 30% or less involves color and most reported completing less than 30 hours of formal color instruction⁹² (including lectures, tutorials and demonstrations).⁹³ Only 66% of educators rated their level of color knowledge (color models, software and color theory) as expert or professional level, while 34% rated themselves as beginners or advanced beginners.⁹⁴

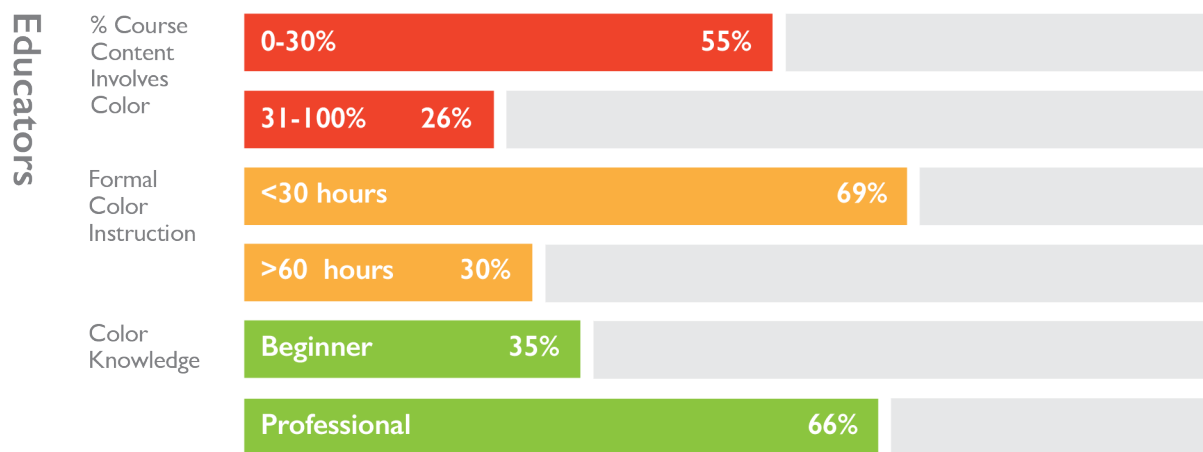


Figure 9: *Survey of design educators*⁹⁵

When asked what changes they recommended to color curricula in design programs, respondents suggested an overall increase in basic color education, that color be addressed at each step of the design process and the inclusion of a required foundation level course devoted to color theory and color application. Respondents also suggested that design

⁹¹ 13% of respondents marked sure/not applicable when rating their satisfaction with the color education at the last institution they attended; Diana Witcher, *What Designers Need to Know About Color* (Survey #2015-09-0131, 2016).

⁹² An average, 3 credit college course is about 45 contact hours

⁹³ 20% of instructors responded with not sure/not applicable

⁹⁴ Diana Witcher, *What Designers Need to Know About Color* (Survey #2015-09-0131, 2016).

⁹⁵ Ibid.

color courses be practice-based and work with tangible color objects. It was further recommended that more color-specific courses be offered and that upper-level classes should include the history of color in art, color trends and real world technical requirements as well as advanced color theory and its practical applications. Finally, designers felt that educational partnerships should be formed with printing and production companies.⁹⁶

In conclusion, the survey revealed that designers believe that color plays an important role in design practice but most designers feel they did not receive adequate, up-to-date color education. Many designers complete their education with only a superficial understanding of color and often must learn about contemporary color systems, standards and management on the job or through independent study after they graduate.

COLOR ARTIFACTS

Designers have a contributory role to play in an integrated understanding of color. A “designerly way” of understanding color focuses on the design process and generates knowledge through the activities of designing and thinking.⁹⁷ Two approaches were used in this inquiry toward this end. First, in-depth research was conducted examining color materials and essential color theory concepts. Second, design process lead to the creation of artifacts through the development of successive prototypes. This project ultimately provides one approach to an ongoing challenge for designers, finding ways to visualize and communicate abstract, complex and relational concepts, like color, in ways that are clear to the average person.⁹⁸

⁹⁶ Diana Witcher, *What Designers Need to Know About Color* (Survey #2015-09-0131, 2016).

⁹⁷ Randy Nakamura, “The Grand Unified Theory of Nothing: Design, the Cult of Science and the Lure of Big Ideas,” in *Looking Closer 5: Critical Writings on Graphic Design*, edited by Michael Bierut, William Drenttel, and Steven Heller (New York: Allworth Press, 2006), 3–8.

⁹⁸ Ibid.

I created a series of toys that suggest one approach to explain color theory through interactive objects made of everyday color materials. Chromatic Primes is a series of toys intended to promote a greater understanding of color by allowing the user to experiment with colored objects. I have used ordinary production techniques and widely used materials like paint, colored acrylic, ink, paper, computer monitor and projected light.

These objects meaningfully integrate color theory and color materials by allowing people to personally experience color concepts. The following series of prototypes demonstrates five color concepts that are essential for designers to understand: 1) *simultaneous contrast* (see figure 11, page 27), 2) *additive color* (light), 3) *subtractive color* (pigment), 4) *transmission and reflection* of colored light and 5) the impact of color on our *perception of value* (relative lightness and darkness).

Chromatic Primes No. 6—Simultaneous Contrast

Chromatic Primes No. 6 (figure 10) demonstrates the concept of *color from pigment* and the phenomenon of *simultaneous contrast*. Each layer consists of three concentric pieces: a central cube, a three-inch frame and a five-inch frame. Each piece has one of six colors on each side. There are four sets of roughly analogous color combinations: red/violet, yellow/orange, green/blue and blue/violet. Each set can produce 216 distinct color combinations. When the four sets are combined, there are twenty-four individual colors. The user can flip the layers to create different color solutions and observe how each color changes when surrounded by different color combinations.



Figure 10: Diana Witcher. *Chromatic Primes No. 6*, 2016.
(Photo courtesy of Victor Tran 2016.)

This toy is inspired by Josef Albers' series of prints and paintings *Homage to the Square*, which he began in 1950 and created over 1,000 variations with different media over 25 years.⁹⁹

Simultaneous contrast describes the interaction of color, the impact of adjacent colors on color appearance. Color interactions are highly unpredictable and hues can look dramatically different due to the impact of surrounding colors.¹⁰⁰ When a gray square is placed on a yellow background it appears gray-violet, but when the same square is placed

⁹⁹ John H. Holloway, John A. Weil and Josef Albers, "A Conversation with Josef Albers," in *Leonardo* (1970): 459–464; and Ann Temkin, *Color Chart: Reinventing Color, 1950 to Today* (New York: The Museum of Modern Art, 2008).

¹⁰⁰ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

on an orange background it seems bluish-gray.¹⁰¹ Colors are not equally impacted by simultaneous contrast; red and yellow are more constant in appearance, while green, blue and violet are more easily influenced.¹⁰²



Figure 11: *Simultaneous contrast*¹⁰³

Chromatic Primes No. 4—Reflection and Transmission

This toy demonstrates the interaction of color and transmission of light in transparent materials. Made of four colors of transparent acrylic, which were heat-molded into shell forms, each is slightly smaller than the next. The objects nest within one another and there are two color sets, 1) warm: purple, red, orange, yellow and 2) cool: blue, light blue, green, light green. The user can arrange the shells in different combinations to observe the interaction of color or place them in a direct light source to demonstrate reflected color and transmission of colored light. Each set can produce 15 distinct color combinations.

Transmissive materials are partially translucent and absorb some wavelengths while allowing others to pass through.¹⁰⁴ *Spectral reflectance* is the degree to which

¹⁰¹ Johannes Itten. *The Elements of Color; A Treatise on the Color System of Johannes Itten, Based on His Book The Art of Color*, edited by Faber Birren (New York: John Wiley & Sons, Inc., 1970).

¹⁰² Lois Swirnonff, *Dimensional Color* (New York & London: W.W. Norton & Co., 2003).

¹⁰³ Image adapted by author from Johannes Itten. *The Elements of Color; A Treatise on the Color System of Johannes Itten, Based on His Book The Art of Color*, edited by Faber Birren (New York: John Wiley & Sons, Inc., 1970).

¹⁰⁴ Bruce, Fraser, Chris Murphy and Fred Bunting, *Real World Color Management: Industrial-Strength Production Techniques* (Berkeley: Peachpit Press: 2009).

an object reflects certain wavelengths and absorbs others.¹⁰⁵ Intensely colored objects reflect color onto the surrounding area.¹⁰⁶ The more reflective the surface, the more vivid the reflected color will be.¹⁰⁷ *Fish Scale Projection* (1998) by Lois Swirnoff, presented in her book *Dimensional Color*, inspired the shell form of this toy.¹⁰⁸



Figure 12: Diana Witcher, *Chromatic Primes No. 4*, 2016.
(Photos courtesy of Victor Tran, 2016).

Chromatic Primes No. 24—Color Impacts Value Perception

This game demonstrates the way color influences our perception of value (relative lightness and darkness). It includes 24 shades of colored marbles (two of each) and a flexible game board (see figure 13). Each player takes turns moving the marbles to complete color challenges: arranging the colors from light to dark, separating the warm and cool colors and selecting individually preferred colors. The game can be played in front of a live video feed with a black and white filter or players can check their work at the end of each round with a black and white app on a cell

¹⁰⁵ Bruce, Fraser, Chris Murphy and Fred Bunting, *Real World Color Management: Industrial-Strength Production Techniques* (Berkeley: Peachpit Press: 2009).

¹⁰⁶ Johannes Itten. *The Elements of Color; A Treatise on the Color System of Johannes Itten, Based on His Book The Art of Color, edited by Faber Birren* (New York: John Wiley & Sons, Inc., 1970).

¹⁰⁷ Ibid.

¹⁰⁸ Lois Swirnoff, *Dimensional Color* (New York & London: W.W. Norton & Co., 2003): 119.

phone or tablet. Color perception varies between individuals and each challenge has more than one correct solution.

Humans distinguish color based upon three attributes: hue, saturation and value.¹⁰⁹ Our perception of value is related to and can be confused by hue, the specific spectral category of a color (i.e. red, green and blue). When we arrange a given set of colors from dark to light and check our work with a black and white camera; we find that we have made mistakes. This is in part because saturated hues do not generally share the same value—yellow is lighter than green and pure red is relatively darker than both.¹¹⁰



Figure 13: Diana Witcher, *Chromatic Primes No. 24*, 2016.
(Photo courtesy of Victor Tran, 2016).

¹⁰⁹ Laurent Busin, Nicolas Vandenbroucke, Ludovic Macaire, "Color Spaces and Image Segmentation," *Advances in Imaging and Electron Physics* 151, no. 1 (2008): 65–168.

¹¹⁰ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

Chromatic Primes No. 7—Additive Color Mixing

Chromatic Primes No. 7 is a light mixing demonstration, which illustrates how the primary colors of light (red, green and blue) combine to create both white light and the secondary colors of light (cyan, magenta and yellow). A projector produces overlapping circles of colored light. First, a green circle overlaps a red circle to create the corresponding light mixture, yellow. Next, a blue circle partially overlaps both circles to show that blue and green light create cyan light, and that all three primary colors result in a central portion of white light. Designers use light mixing, or additive color, through computer screens, mobile devices, video display and projection.¹¹¹



Figure 14: Diana Witcher, *Chromatic Primes No. 7*, 2016.
(Photo courtesy of Victor Tran, 2016).

¹¹¹ Laurent Busin, Nicolas Vandenbroucke, Ludovic Macaire, "Color Spaces and Image Segmentation," *Advances in Imaging and Electron Physics* 151, no. 1 (2008): 65–168.

Ten Important Color Concepts for Designers

Although centuries-old theories and color models are still useful for understanding and using color, they are not sufficient for designers today working in fields like graphic design, industrial design, architecture and interior design. The technical complexity of color in design practice is the reason that “the designer who understands color has a competitive edge in every industry.”¹¹² This section briefly outlines important concepts from different disciplines that designers should be aware of including: 1) Color theory and physics, 2) Additive color theory (RGB and HSV color models), 3) Subtractive color theory (RYB and CMY color models), 4) Color spaces, 5) Digital color and ICC profiles, 6) Color image formats, 7) Color management, 8) Color organizations, 9) Color order systems and 10) Color tools.

1. Color Theory and Physics—What is Color?

Designers who have a basic understanding of color physics, the properties of light and its interaction with materials and surfaces, are better able to conceptualize the problems of color in practice. A more complete understanding of color exists at the intersection of physiology, psychology and physics.¹¹³ The term *color* encompasses three distinct ideas: first, it is a *descriptive property* of an object, “the lemon is yellow,” secondly it is a *quality of light*, “the lemon reflects yellow light and absorbs other wavelengths” and thirdly defines a *class of sensations*, the brain’s interpretation of the light the eye perceives as it is reflected from the lemon.¹¹⁴

¹¹² Linda Holtzschue, *Understanding Color: an Introduction for Designers* (New York: John Wiley & Sons, 2012), 3.

¹¹³ Sally Cochrane, "The Munsell Color System: A Scientific Compromise from the World of Art, Part A," *Studies in History and Philosophy of Science*, 47 (2014): 26–41.

¹¹⁴ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley-Interscience, 2001).

Color is generated by light and in the absence of light color is nonexistent.¹¹⁵ Sunlight is perceived as white or colorless, but when it passes through a prism or other refractive material the component colors of the spectrum are revealed.¹¹⁶ Physical light is visible energy that is produced by light sources and behaves as waves or pulses; it travels at a constant speed, but is emitted at different frequencies.¹¹⁷ Wavelengths are the distance between the peaks or waves of energy and are measured in nanometers (nm).¹¹⁸ The quality and intensity of reflected light is determined by a combination of object reflectance, object geometry and the light source that illuminates the object.¹¹⁹ While the quality of light dramatically influences color perception, *color constancy* is the ability to accurately differentiate hue in a wide variety of lighting conditions.¹²⁰ The receptors that perceive color in low light allow us to recognize specific colors independent of variations in ambient light.¹²¹

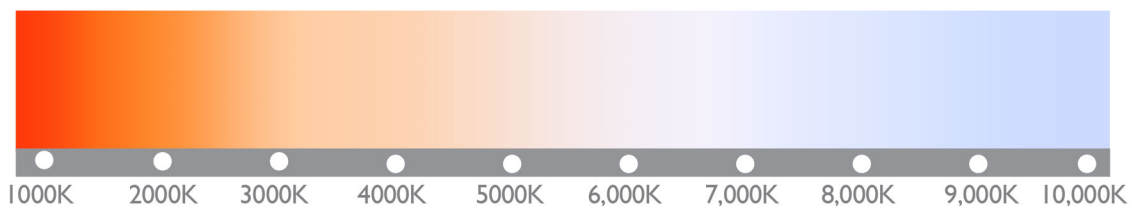


Figure 15: *Correlated color temperature in kelvins*¹²²

¹¹⁵ Linda Holtzschue, *Understanding Color: an Introduction for Designers* (New York: John Wiley & Sons, 2012).

¹¹⁶ Ibid.

¹¹⁷ Matthew Luckiesh, *Color and its Applications* (New York: D. Van Nostrand Company, 1921).

¹¹⁸ Linda Holtzschue, *Understanding Color: an Introduction for Designers* (New York: John Wiley & Sons, 2012).

¹¹⁹ Jan-Mark Geusebroek, et al., "Color Constancy from Physical Principles," *Pattern Recognition Letters* 24, no. 11 (2003): 1653–1662.

¹²⁰ Edwin H. Land and John J. McCann, "Lightness and Retinex Theory," *Journal of the Optical Society of America* 61, no. 1 (1971): 1–11.

¹²¹ Ibid.

¹²² Image adapted by author from "Color Temperature of a Black Body," *Wikimedia Creative Commons*, October 13, 2015, accessed June 8, 2016, https://commons.wikimedia.org/wiki/File:Color_temperature_black_body_mired.svg.

Correlated color temperature is measured in *kelvins* (K) and describes the quality of white light. *Color temperature index* describes the relative color of light as warm, cool or neutral (see figure 15).¹²³ An incandescent light bulb emits yellowish light of about 2850 to 3100K, white light is 5000 to 7000 (K) while anything above 9000 K is a bluish light.¹²⁴

2. Additive Color Theory: RGB and HSV Color Models

Understanding additive color theory helps designers to better grasp its application in design programs, photography, and color matching as well as the use of light media (monitors, mobile devices and light installations). Color models (i.e. RYB, RGB, HSV, CMYK) are broad, categorical ways to mathematically describe colors by defining them within a coordinate space, typically with three to four numeric values.

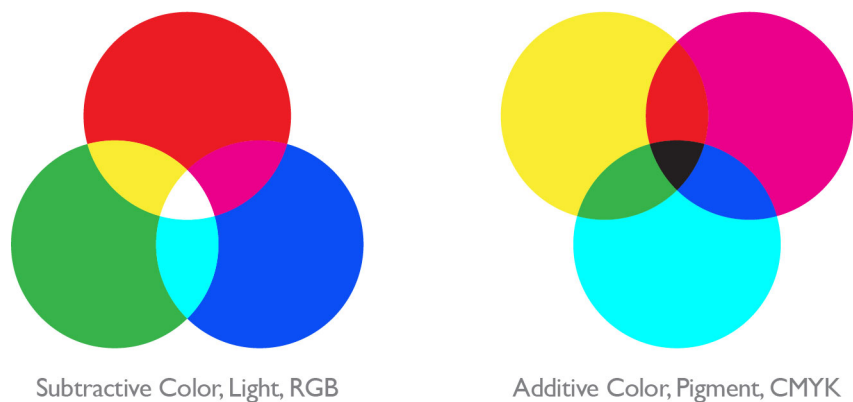


Figure 16: *RGB and CMYK color models*¹²⁵

¹²³ Karen Triedman, *Colour: The Professional's Guide: Understanding and Mastering Colour in Art and Design* (London: Ilex Press, 2015).

¹²⁴ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004.)

¹²⁵ Image adapted by author from Mike Horvath, "Additive Color Mixing," *Wikimedia Creative Commons*, October 26, 2006, accessed June 23, 2016, <https://commons.wikimedia.org/wiki/File:AdditiveColor.svg>; and Mike Horvath, "Subtractive Color," *Wikimedia Creative Commons*, October 26, 2006, accessed June 23, 2016, <https://commons.wikimedia.org/wiki/File:SubtractiveColor.svg>.

The RGB color model is the basis of RGB working spaces, which include sRGB and Adobe RGB (1998).¹²⁶ As demonstrated in Chromatic Primes No. 7, the primary colors of light are red, green and blue (RGB), and the secondary colors of light are cyan (blue and green), yellow (red and green) and magenta (yellow and red).¹²⁷ This model is the basis for color on the color monitor, the tool designers use daily for design production. The computer user draws and paints with light, rendering directly in additive colors.¹²⁸

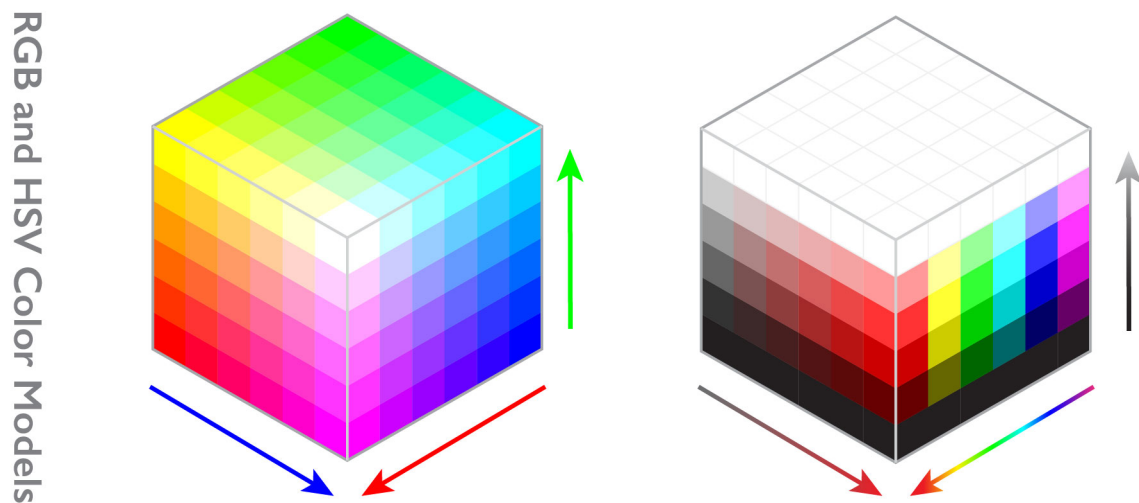


Figure 17: *Comparison of RGB and HSV color models*¹²⁹

¹²⁶ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

¹²⁷ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley-Interscience, 2001).

¹²⁸ Linda Holtzschue, *Understanding Color: an Introduction for Designers* (New York: John Wiley & Sons, 2012).

¹²⁹ Image adapted by author from Michael Horvath, "HSL Color Mapped to a Cube," *Wikimedia Creative Commons*, December 28, 2015, accessed June 25, 2016, https://commons.wikimedia.org/wiki/File:HSL_color_solid_cube.png; Michael Horvath, "The RGB Color Model Mapped to a Cube" *Wikimedia Creative Commons*, December 28, 2015, accessed June 25, 2016, https://commons.wikimedia.org/wiki/File:HSL_color_solid_cube.png; and Brandon Mathis, "A Most Excellent HSL Color Picker," 2012, accessed June 25, 2016, <http://hslpicker.com>.

HSV (HSB) Color Model

The HSV (hue, saturation and value) color model is a transformation of the RGB color model most commonly used in color picker tools found in Photoshop and other imaging software.¹³⁰ It is sometimes referred to as HSB for hue, saturation, and brightness.¹³¹ HSV is useful to easily match a large range of colors based upon perception.¹³²

3. Subtractive Color (Pigment): RYB and CMY Color Models

Art and design students are usually taught pigmentary or *subtractive* color.¹³³ Perceived colors are determined by the light wavelengths reflected by an object's surface.¹³⁴

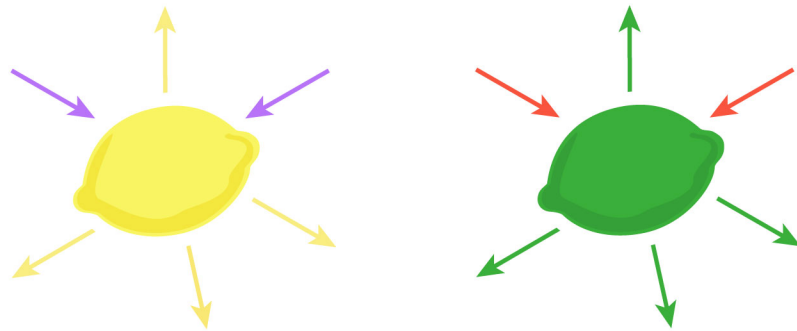


Figure 18: *Subtractive color from pigment*¹³⁵

Pigment is the most common source of color in objects.¹³⁶ It reflects the wavelengths of the visible color and absorbs the wavelengths that are complementary (or opponent) to the

¹³⁰ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

¹³¹ Ibid.

¹³² Ibid.

¹³³ Verner Panton et al., *Verner Panton* (Basle, Switzerland: Basler Zeitung, 1998).

¹³⁴ Ibid.

¹³⁵ Image by author from explanation of subtractive color by Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color, 2nd ed.* (New York: Wiley-Interscience, 2001).

¹³⁶ Hilda Simon, *Color in Reproduction: Theory and Techniques for Artists and Designers* (New York: Viking Press, 1980).

visible color (see figure 18).¹³⁷ The greater the amount of pigment present in a surface, the less light is reflected back to the observer, resulting in a darker color.¹³⁸ When an object reflects over 80 to 90% of the light falling on it, we perceive it as white and when it absorbs more than 95% of the light it appears black.¹³⁹ Each subtractive primary absorbs about one third of the light spectrum, while all three together absorb almost 100%.¹⁴⁰

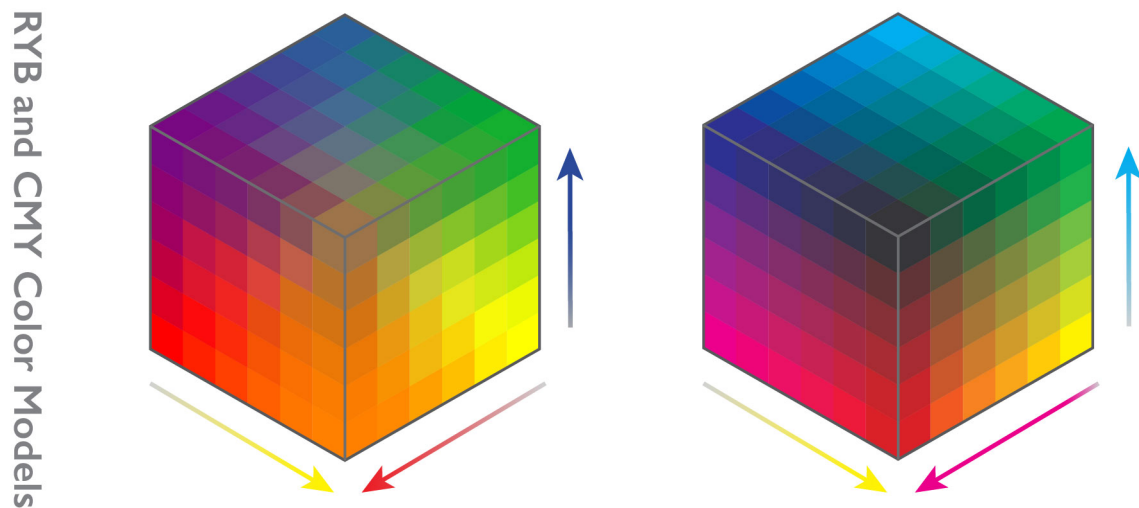


Figure 19: *Comparison of RYB and CMY color models*¹⁴¹

The *RYB color model* is commonly used by painters and was developed by color theorists including Newton, Goethe, Chevreul and Itten.¹⁴² The traditional primary colors of

¹³⁷ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley-Interscience, 2001).

¹³⁸ Hilda Simon, *Color in Reproduction: Theory and Techniques for Artists and Designers* (New York: Viking Press, 1980).

¹³⁹ Verner Pantón et al., *Verner Pantón* (Basle, Switzerland: Basler Zeitung, 1998).

¹⁴⁰ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley-Interscience, 2001).

¹⁴¹ Image adapted by author from Dave Eddy, “RYB Color Wheel,” *GitHub*, accessed June 25, 2016, <http://bahamas10.github.io/ryb/>; Horst Frank, “CMYK Farbwuerfel,” *Wikimedia Creative Commons*, November 14, 2004, accessed June 25, 2016, https://commons.wikimedia.org/wiki/File:CMYK_farbwuerfel.jpg; and “HTML Color Mixer,” *W3 Schools*, accessed June 25, 2016, http://www.w3schools.com/colors/colors_mixer.asp.

¹⁴² Verner Pantón et al., *Verner Pantón* (Basle, Switzerland: Basler Zeitung, 1998); and Edith Anderson Feisner and Ronald Reed, *Color Studies*, 3rd ed. (New York: Fairchild Publications, Inc., 2013).

red, yellow and blue (RYB) are organized into the color wheel and are mixed to create the other hues.¹⁴³ Designers, printers and photographers frequently use *the CMY color model*, which organizes the true subtractive primaries: cyan, magenta and yellow.¹⁴⁴ This system is more effective in producing a full range of spectral colors than the traditional RYB model.¹⁴⁵

4. Color Spaces

While color model and color space are often used synonymously, *color spaces* are tools to pragmatically use and specify colors, meaningfully integrating a given color model with real world colors. Color spaces geometrically map and specify a range of colors, often with three numeric values.¹⁴⁶ The first color spaces denoted colors based upon human perception, were typically three-dimensional and organized colors with color charts and color atlases.¹⁴⁷ These color spaces use component units to specify colors and include the CIEXYZ color space, the Optical Society of America (OSA) system, and commercial color spaces like the Natural Color System (NCS) and the Munsell system.¹⁴⁸ (NCS and Munsell are discussed in more detail as color order systems—see number 9.)

Device color spaces are mathematical models, which precisely describe the *gamut* (limited color range) of specific devices (see number 7, page 45).¹⁴⁹ They are tools for understanding the color capabilities of digital files and devices and maintaining quality in

¹⁴³ Edith Anderson Feisner and Ronald Reed, *Color Studies*, 3rd ed. (New York: Fairchild Publications, Inc., 2013).

¹⁴⁴ Ibid.

¹⁴⁵ Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, 2nd ed. (New York: Wiley-Interscience, 2001).

¹⁴⁶ Laurent Busin, Nicolas Vandenbroucke, Ludovic Macaire, "Color Spaces and Image Segmentation," *Advances in Imaging and Electron Physics* 151, no. 1 (2008): 65–168.

¹⁴⁷ Laurent Busin, Nicolas Vandenbroucke, Ludovic Macaire, "Color Spaces and Image Segmentation," *Advances in Imaging and Electron Physics* 151, no. 1 (2008): 65–168; and Sabine Süsstrunk, Robert Buckley and Steve Swen, "Standard RGB Color Spaces," in *Color and Imaging Conference* 1999, no. 1 (1999): 127–134.

¹⁴⁸ Laurent Busin, Nicolas Vandenbroucke, Ludovic Macaire, "Color Spaces and Image Segmentation," *Advances in Imaging and Electron Physics* 151, no. 1 (2008): 65–168.

¹⁴⁹ Ibid.

color reproduction.¹⁵⁰ Device color spaces only address the colors that a device can generate and are referred to as dRGB (device RGB) for scanners and cameras or dCMYK for printers.¹⁵¹

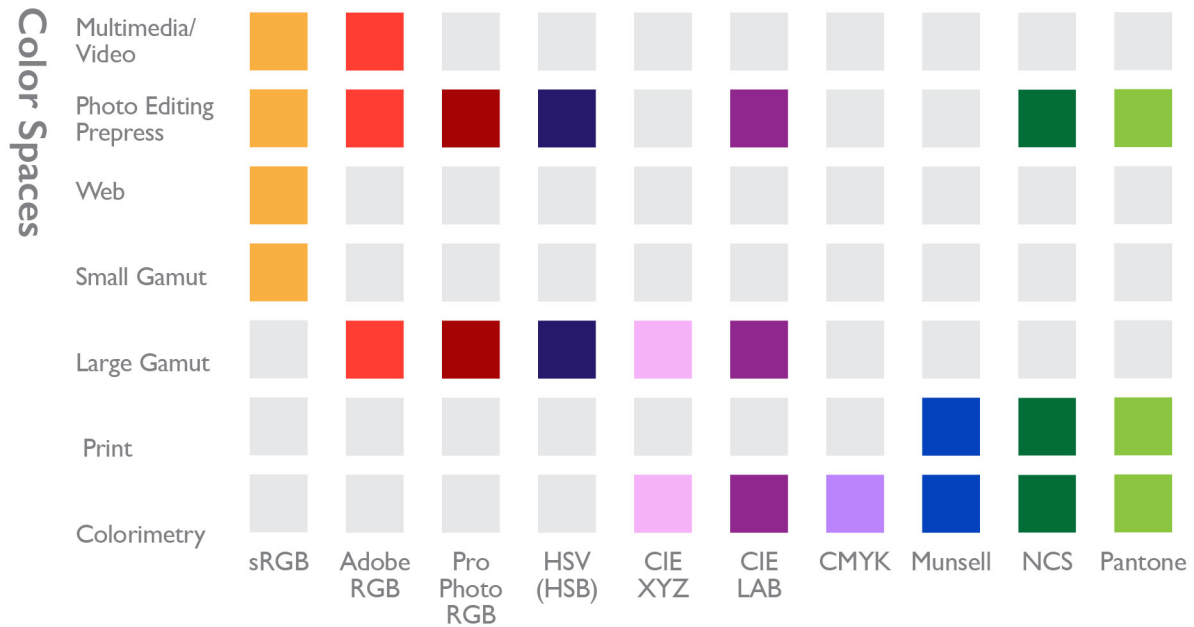


Figure 20: *Applications and media of color spaces*¹⁵²

Adobe RGB (1998), sRGB, LAB, CMYK, and HSV (HSB) are the most commonly used *working color spaces*, which are applied when creating a new document or opening a file with no specified color space.¹⁵³ *RGB working color spaces* like sRGB and Adobe RGB (1998) are device independent, meaning that they are not associated

¹⁵⁰ Ján Morovič, *Color Gamut Mapping* (Chichester, England: John Wiley & Sons, 2008), 73–76.

¹⁵¹ János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: John Wiley & Sons, 2007).

¹⁵² Image data from the following sources: Steven Bleicher, *Contemporary Color: Theory and Use* (Clifton Park, NY: Delmar, Cengage Learning, 2011); Laurent Busin, Nicolas Vandenbroucke, Ludovic Macaire, "Color Spaces and Image Segmentation," *Advances in Imaging and Electron Physics* 151, no. 1 (2008): 65–168; János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: John Wiley & Sons, 2007); and Sabine Süssstrunk, Robert Buckley and Steve Swen, "Standard RGB Color Spaces," in *Color and Imaging Conference 1999*, no. 1 (1999): 127–134.

¹⁵³ Steven Bleicher, *Contemporary Color: Theory and Use* (Clifton Park, NY: Delmar, Cengage Learning, 2011).

with a particular device like a monitor or printer.¹⁵⁴ Adobe RGB (1998) has a larger gamut than sRGB, which is the standard color space for the Internet and monitors, as well as many cameras and printers.¹⁵⁵ The sRGB gamut is smaller than the range of colors that can be achieved by quality color print production.¹⁵⁶ Working spaces with wider gamuts preserve more color information but can also increase the potential for visible artifacts because they include colors that cannot be rendered in sRGB monitors or printed in CMYK.¹⁵⁷ The HSV (HSB) color space is most commonly used in color selection tools for imaging software.¹⁵⁸ It is also the basis of the “curves” dialog in Photoshop, used to change the output of a selected RGB color channel.¹⁵⁹

Color spaces that describe an estimate of the original colorimetry of a scene or object include CIEXYZ, ISORGB and CIELAB.¹⁶⁰ The CIEXYZ and CIELAB color spaces are equivalent to the range of human color perception and they are device independent.¹⁶¹ CIELAB is uniform (the distances between colors correspond to perceived color differences).¹⁶² CIELAB is important as the basis of color correction in programs like

¹⁵⁴ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

¹⁵⁵ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

¹⁵⁶ Sabine Süsstrunk, Robert Buckley and Steve Swen, “Standard RGB Color Spaces,” in *Color and Imaging Conference 1999*, no. 1 (1999): 127–134.

¹⁵⁷ Ibid.

¹⁵⁸ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

¹⁵⁹ Ibid.

¹⁶⁰ Sabine Süsstrunk, Robert Buckley and Steve Swen, “Standard RGB Color Spaces,” in *Color and Imaging Conference 1999*, no. 1 (1999): 127–134.

¹⁶¹ International Color Consortium, “Image Technology Colour Management—Architecture, Profile Format, and Data Structure,” *Specification 201*, no. 1, International Color Consortium (2006): 2004–2010, accessed July 1, 2016, http://www.color.org/ICC1v42_2006-05.pdf.

¹⁶² Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

Photoshop and Lightroom, it describes color in terms of *l* (lightness), *a* (red–green), and *b* (yellow–blue) opponent pairs.¹⁶³ LAB is also used for ICC profiles (see number 7).¹⁶⁴

5. Digital Color

Designers need to have a basic understanding of how color works in the digital realm. In the digital era, color is commonly produced and experienced through color software and various imaging devices including computers, cell phones, digital cameras, television screens, printers and projectors.¹⁶⁵

Graphics software is of two major types: raster and vector. *Raster-based* programs, like Adobe Photoshop and Lightroom, are resolution-dependent and use pixels.¹⁶⁶ Problems occur during image editing when the computer program algorithm approximates pixels, causing images to become pixilated or blurry.¹⁶⁷ *Vector-based programs* like Adobe Illustrator, InDesign, Flash and CorelDRAW create images using a mathematical formula or algorithm.¹⁶⁸ These designs can be resized without loss of image quality, so they are preferred for logo design, typesetting and illustration, but they cannot be printed accurately with most printers without a special kind of driver called a RIP.¹⁶⁹

A bit is the smallest unit of information (0s and 1s) and is the basis for binary code in information systems.¹⁷⁰ Bit depth, or color depth, is the number of bits used to

¹⁶³ János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: John Wiley & Sons, 2007).

¹⁶⁴ Phil Green, *Color Management: Understanding and Using ICC Profiles* (Chichester & West Sussex, U.K.: Wiley, 2010).

¹⁶⁵ Lev Manovich, *The Language of New Media* (Cambridge: MIT Press, 2001).

¹⁶⁶ Steven Bleicher, *Contemporary Color: Theory and Use* (Clifton Park, NY: Delmar, Cengage Learning, 2011).

¹⁶⁷ Ibid.

¹⁶⁸ Ibid.

¹⁶⁹ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014); and Steven Bleicher, *Contemporary Color: Theory and Use* (Clifton Park, NY: Delmar, Cengage Learning, 2011).

¹⁷⁰ Ibid.

denote the range of possible color values assigned to each pixel.¹⁷¹ Most color monitors now support true color, which has twenty-four bits and provides 16 million different colors.¹⁷² The following are the number of discrete colors produced by different bit depths:

- 8 bit—256 colors
- 16 bit—High Color, 65,536 colors
- 24 bit—True Color, 16,777,216 colors
- 32 bit—True Color, 4,294,967,296 colors¹⁷³

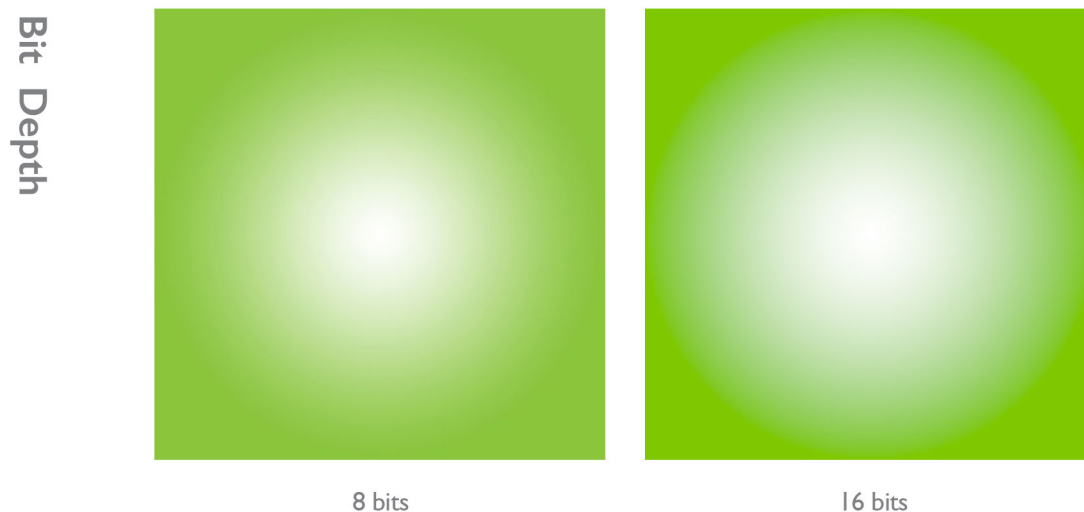


Figure 21: *Comparison of 8 bit depth and 16 bit depth images*¹⁷⁴

¹⁷¹ Dan Oja and June Jamrich Parsons, *Computer Concepts: Illustrated Brief*, 8th ed. (Boston: Course Technology, Cengage Learning, 2010).

¹⁷² Steven Bleicher, *Contemporary Color: Theory and Use* (Clifton Park, NY: Delmar, Cengage Learning, 2011).

¹⁷³ Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf.

¹⁷⁴ Image adapted by author from: Andrew Gibson, “Bit Depth Explained In-depth,” Envato Pty Ltd. (2012), accessed June 10, 2016, <http://photography.tutsplus.com/articles/bit-depth-explained-in-depth--photo-8514>.

Files saved and edited in lower bit depths display a limited color range and often exhibit visual artifacts like color banding.¹⁷⁵ Images saved and edited in higher bit depths display a wider range of colors and provide more precise and rich color representation.¹⁷⁶

6. Color Image Formats

Color image formats are the medium in which designers edit, store and convey color information between devices, users, interfaces and outputs. Understanding image formats is key to producing excellent color results.

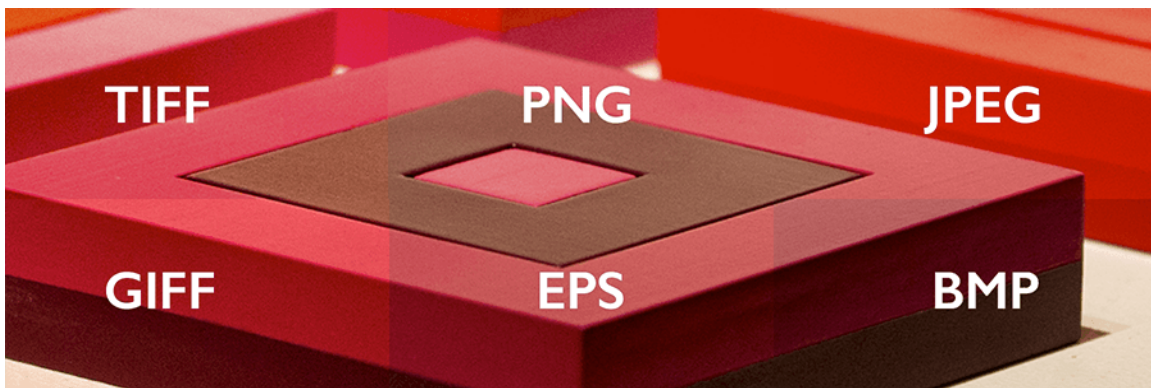


Figure 22: *Image formats impact digital color output*
(Image adapted from photo courtesy of Victor Tran, 2016).

Color images are stored in raster, vector or compound image formats. Raster graphics store graphic images as pixel values at a fixed resolution.¹⁷⁷ The most common raster formats include TIFF, GIF, JPEG and PNG.¹⁷⁸ Vector formats, like SVG, contain a description of

¹⁷⁵ Judith A. Birchman and Susan G. Miller, "Preparing Images for Distribution," *Engineering Design Graphics Journal* 64, no. 1 (2009): 35–44; and Ron Brinkmann, *The Art and Science of Digital Compositing* (Amsterdam: Elsevier Morgan Kaufmann, 2011).

¹⁷⁶ Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf.

¹⁷⁷ Frank Klawonn, *Introduction to Computer Graphics: Using Java 2D and 3D* (New York: Springer, 2012).

¹⁷⁸ Alejandro C. Frery and Talita Perciano, "Image Data Formats and Color Representation," in *Introduction to Image Processing Using R: Learning by Examples* (London: Springer, 2013), 21–29.

shapes and elements on a page.¹⁷⁹ Vector files are resolution independent and are infinitely scalable, but cannot always be printed accurately from standard printer drivers.¹⁸⁰ Compound formats like PDF and EPS store images with both vector and pixel data.¹⁸¹

Color Image Formats	Max Bit Depth	32	8	16	16	16		32		16	16
	Line Art/ Logos										
	HD Photo										
	Web										
	Print										
	Lossy										
	Lossless										
	Compressed										
	Raw or Uncompressed										
	Transparency										
	* Vector	TIFF	GIF	JPEG	JPEG 2000	PNG	EPS*	BMP	SVG*	RAW	PDF*

Figure 23: Color image formats, their attributes and use¹⁸²

¹⁷⁹ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

¹⁸⁰ Ibid.

¹⁸¹ Wilhelm Burger and Mark James Burge, *Principles of Digital Image Processing: Advanced Methods* (London: Springer, 2013).

¹⁸² Image data from the following sources: Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf; Wilhelm Burger and Mark James Burge, *Principles of Digital Image Processing: Advanced Methods* (London: Springer, 2013); Jessica Fridrich, Miroslav Goljan and Rui Du, "Lossless Data Embedding for All Image Formats," in *Electronic Imaging 2002*, International Society for Optics and Photonics (2002): 572–583; Richard N. J. Graham, R.W. Perriss, and Andrew F. Scarsbrook, "DICOM Demystified: A Review of Digital File Formats and Their Use in Radiological

Two types of image compression algorithms are used to reduce file size for color image storage and data transmission.¹⁸³ Lossless compression reduces file size without any loss of color information; these files are larger and slower to open and save.¹⁸⁴ Lossy image compression results in dramatic reduction in file size by permanently eliminating some of the file data and can adversely impact image quality.¹⁸⁵ Some file formats support both lossless and lossy compression.

Uncompressed file formats like TIFF, JPEG 2000 and PDF preserve the original image color data.¹⁸⁶ RAW files contains unprocessed, uncompressed image data from a digital camera's image sensor, when you adjust a raw image in Photoshop, the original image data is preserved and adjustments are stored as metadata but don't degrade the image.¹⁸⁷ Choosing the correct image format is essential. For example, when editing a photo saved in JPEG format, important color information is lost that would be retained with a lossless format like RAW.¹⁸⁸

7. Color Management and ICC profiles

Color management is the process of translating color information between source and destination devices for optimum color results.¹⁸⁹ No device is capable of reproducing the full

Practice," *Clinical Radiology*. 60, no. 11 (2005): 1133–1140; and Li Kuo Tan, "Image File Formats," *Biomed Imaging Intervention Journal* 2, no. 1 (2006): e6.

¹⁸³ Richard N. J. Graham, R.W. Perriss, and Andrew F. Scarsbrook, "DICOM Demystified: A Review of Digital File Formats and Their Use in Radiological Practice," *Clinical Radiology*. 60, no. 11 (2005): 1133–1140; and Li Kuo Tan, "Image File Formats," *Biomed Imaging Intervention Journal* 2, no. 1 (2006): e6.

¹⁸⁴ Ibid.

¹⁸⁵ Jon Tarrant, *Digital Camera Techniques* (Burlington, MA: Focal Press, 2013).

¹⁸⁶ Ibid.

¹⁸⁷ Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf; and Jon Tarrant, *Digital Camera Techniques* (Burlington, MA: Focal Press, 2013).

¹⁸⁸ Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf.

¹⁸⁹ Ján Morovič and Johan Lammens, "Color Management," in *Colorimetry: Understanding the CIE System*, ed. János Schanda (Hoboken, NJ: Wiley-Interscience, John Wiley & Sons, Inc., 2007), 159–206.

range of colors visible to the human eye.¹⁹⁰ Each device utilizes a specific device color space (i.e. dRGB or dCMYK) and generates a limited range of colors, or gamut.¹⁹¹

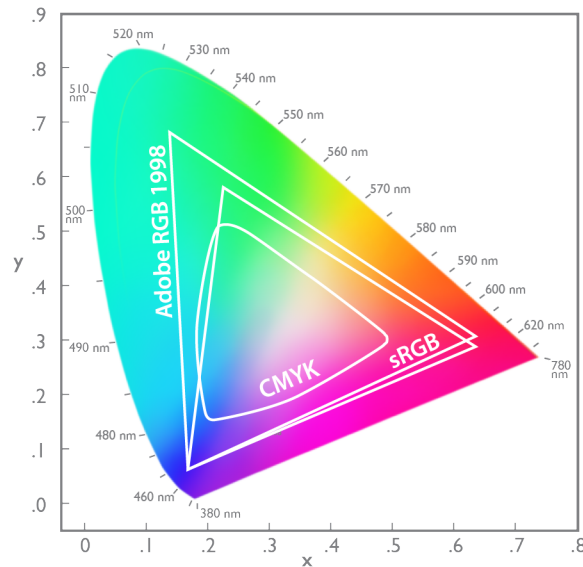


Figure 24: *Approximate color gamuts*¹⁹²

ICC Profiles

ICC profiles characterize the color gamut that a device or process can recognize, display or produce through standardized profile formats.¹⁹³ Device profiles are associated with a specific device such as a monitor or a printer, and sometimes, particular ink and paper.

¹⁹⁰ Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf.

¹⁹¹ Ján Morovič and Johan Lammens, "Color Management," in *Colorimetry: Understanding the CIE System*, ed. János Schanda (Hoboken, NJ: Wiley-Interscience, John Wiley & Sons, Inc., 2007), 159–206.

¹⁹² Image adapted by author from Academo, "Wavelength to Colour Relationship," *Academo.org*, accessed April 24, 2016, <https://academo.org/demos/wavelength-to-colour-relationship>; Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014); János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: John Wiley & Sons, 2007: 9); Public Domain, "CIE 1931 xy Chromaticity Diagram," *Wikimedia Creative Commons*, June 21, 2005, accessed March 10, 2016, <https://commons.wikimedia.org/wiki/File:CIExy1931.png>; and "CIE1931 xy Gamut Comparison," *Wikimedia Creative Commons*, April 14, 2014, accessed March 10, 2016, https://commons.wikimedia.org/wiki/File:CIE1931xy_gamut_comparison.svg.

¹⁹³ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

They describe how each device displays color and which colors it can and can't display. *Working profiles* determine the colors represented in a document and describe how the RGB values in the document correspond to the colors that we see.¹⁹⁴ The two working profiles that are most commonly used are AdobeRGB and sRGB.¹⁹⁵

Color Management Workflow

Designers need to know how to manage workflow for color production. Color management workflow is the process of defining colors through the numeric systems provided by design programs and managing those colors through the stages of image capture, editing and output.¹⁹⁶ This concept applies to three areas, color management within a given program, flow of documents between programs and flow of color materials into or out of a color-managed environment.¹⁹⁷

For example, a photographer must decide whether to capture images in sRGB or Adobe RGB. Designers decide whether to edit images in Adobe RGB, sRGB or CMYK and then must convert files to appropriate file formats and color standards for output.¹⁹⁸ Editing images in a larger bit depth, like 16 bits, and a working space with a larger gamut, like Adobe RGB (1998), is generally recommended in order to preserve the most color information.¹⁹⁹ Converting images to an appropriate output profile (sRGB for web and CMYK or sRGB for print) optimizes color for specific media or devices.

¹⁹⁴ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

¹⁹⁵ Ibid.

¹⁹⁶ Bruce Fraser, Chris Murphy and Fred Bunting, *Real World Color Management: Industrial-Strength Production Techniques* (Berkeley: Peachpit Press: 2009).

¹⁹⁷ Ibid.

¹⁹⁸ Michael Langford, Anna Fox and Richard Sawdon Smith, *Langford's Basic Photography*, 9th Edition, (New York and London: Focal Press, Taylor and Francis, 2013); and Rob Sheppard, *Adobe Camera Raw for Digital Photographers Only*, Vol. 2 (Indianapolis: Wiley Publishing, Inc., 2011).

¹⁹⁹ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

For commercially printed documents, printers can provide the correct output profile for a specific printing device.²⁰⁰ Designers can coordinate color management and workflows both individually and across collaborative teams by calibrating monitors, configuring software and hardware and adding or updating color profiles for input and output devices like scanners and printers.²⁰¹



Figure 25: *CMYK vs. RGB color output*
(Image adapted by author from photo courtesy of Victor Tran, 2016).

Designers must also evaluate color results in both print and digital projects.²⁰² Because the color and light of the work environment impacts color perception, documents should be viewed and evaluated in a consistent level of light with a constant color temperature, ideally with a D50 (5000° Kelvin) light box or D50 lighting installed in the studio.²⁰³

²⁰⁰ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

²⁰¹ Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf.

²⁰² Ibid.

²⁰³ Adobe, *Adobe® Photoshop® CC Help*, Adobe Systems, Inc. (2015): 1–915, accessed July 1, 2016, https://helpx.adobe.com/pdf/photoshop_reference.pdf; and Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

Color Printing

Print color quality is a complex topic, worthy of much more detailed treatment, but here are some of the practical concepts designers need to know. *Spot colors* are solid areas of ink that are printed in a single run and include those found in the Pantone Matching System.²⁰⁴ Spot color matching is highly dependent upon the finish of paper stock (coated, uncoated or matte).²⁰⁵ *Process colors* are achieved through the four-color process.²⁰⁶ To create a full-color image, a file is separated into four colors: Cyan (C), Magenta (M), Yellow (Y) and Black (K).²⁰⁷

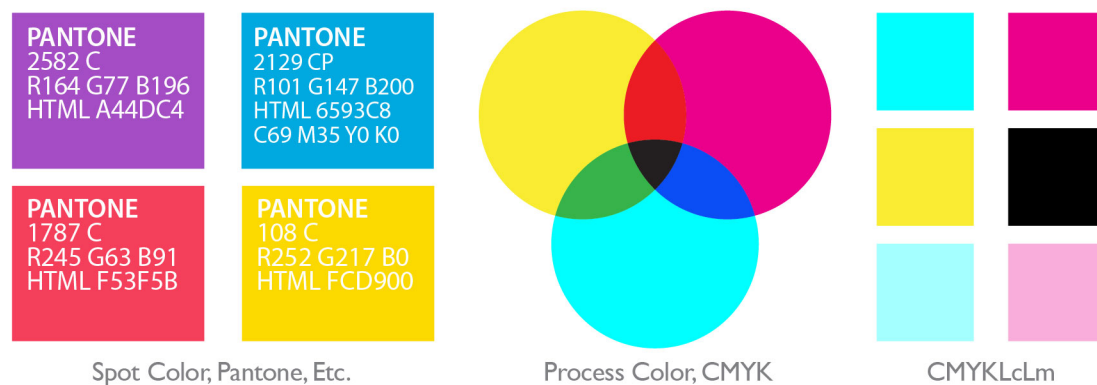


Figure 26: *Spot color vs. process color*²⁰⁸

As each color overprints the next, a composite image emerges.²⁰⁹ Printing 100% black often results in a light, flat black tone, to combat this, designers use rich black, for example

²⁰⁴ Eddie Opara and John Cantwell, *Best Practices for Graphic Designers, Color Works: Right Ways of Applying Color in Branding, Wayfinding, Information Design, Digital Environments and Pretty Much Everywhere Else* (Beverly, MA: Rockport Publishers, 2014).

²⁰⁵ Ibid.

²⁰⁶ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

²⁰⁷ Ibid.

²⁰⁸ Image adapted by author from Pantone, LLC, "Find a PANTONE Color," 2016, accessed June 10, 2016, <http://www.pantone.com/color-finder>; Mike Horvath, "Additive Color Mixing," *Wikimedia Creative Commons*, October 26, 2006, accessed June 23, 2016, <https://commons.wikimedia.org/wiki/File:AdditiveColor.svg>; and Chang-Hwan Son, et al., "Six-color Separation for Improving Graininess in a Middle Tone Region," *Electronic Imaging* 2004 (2003): 110–120.

30C, 30M, 30Y, 100K.²¹⁰ Some contemporary inkjet printers systems known as CcMmYK and CMYKLcLm achieve more accurate color representation by using additional colored inks such as light cyan and light magenta.²¹¹

8. Color Organizations

International Color Consortium

Managing and communicating color in an unambiguous way is one of the major concerns of the imaging industry.²¹² The International Color Consortium (ICC) was founded in 1993 to develop standard profile formats for digital color management. Founding members include Adobe Systems Inc., Apple Computer, Eastman Kodak Company and Microsoft Corporation.²¹³ The ICC provides technical specifications for standard profile formats for operating systems, platforms and applications and specifies a convention for embedding color profiles within images and graphics documents.²¹⁴ This allows for accurate, manageable communication of color between devices.

Other Color Organizations

There are numerous national and international color groups for the arts, sciences and industry that conduct color research and provide color systems, color education and essential

²⁰⁹ Tom P. Ashe, *Color Management & Quality Output: Working with Color from Camera to Display to Print* (New York & London: Focal Press, 2014).

²¹⁰ Jim Krause, *Color for Designers: Ninety-five Things You Need to Know when Choosing and Using Colors for Layouts and Illustrations* (San Francisco: New Riders, Peachpit: 2014).

²¹¹ Chang-Hwan Son, et al., "Six-color Separation for Improving Graininess in a Middle Tone Region," *Electronic Imaging 2004* (2003): 110–120.

²¹² Sabine Süssstrunk, Robert Buckley and Steve Swen, "Standard RGB Color Spaces," in *Color and Imaging Conference 1999*, no. 1 (1999): 127–134.

²¹³ International Color Consortium, "Image Technology Colour Management—Architecture, Profile Format, and Data Structure," *Specification 201*, no. 1, International Color Consortium (2006): 2004–2010, accessed July 1, 2016, http://www.color.org/ICC1v42_2006-05.pdf.

²¹⁴ Ibid.

color tools for professionals.²¹⁵ The Inter-Society Color Council (ISCC) is a professional association for the field of color based in the United States. Founded in 1931, its mission is to advance color knowledge in the arts, sciences and industry. Member groups include the Color Association of the United States, Inc. (CAUS), Color Marketing Group (CMG), the International Color Consortium (ICC) and the Optical Society of America (OSA), but the group is largely comprised of individual members.²¹⁶ The aforementioned CIE, Commission Internationale de l'Eclairage (1913) is the principal international authority for color measurement standards in science and industry.²¹⁷

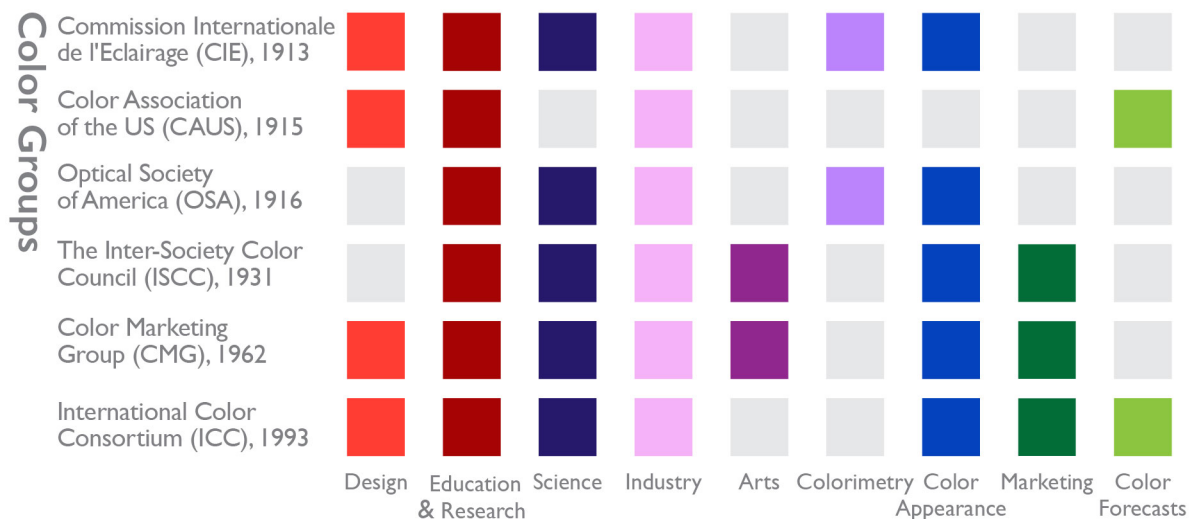


Figure 27: Areas of focus of major color organizations²¹⁸

²¹⁵ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge & London: MIT Press, 2012).

²¹⁶ Inter-Society Color Council, "Inter-Society Color Council: Where Art, Science and Industry Meet," *Inter-Society Color Council*, 2015, accessed May 15, 2016, <http://www.iscc.org/pdf/Brochure2015.pdf>.

²¹⁷ János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: John Wiley & Sons, 2007).

²¹⁸ Information from: CIE—Commission Internationale de l'Eclairage, accessed June 20, 2016, <http://www.cie.co.at>; Color Association of the United States, "About," accessed May 1, 2016, <http://www.colorassociation.com/pages/2-about>; Color Marketing Group, "About Color Marketing Group," accessed May 1, 2016, <http://www.colormarketing.org/about-cmg>; International Color Consortium, "Image Technology Colour Management—Architecture, Profile Format, and Data Structure," *Specification 201*, no. 1, International Color Consortium (2006): 2004-2010, accessed July 1, 2016, http://www.color.org/ICC1v42_2006-05.pdf; OSA,

9. Color Order Systems

Color order systems are “dictionaries of color” which facilitate effective color communication and color management.²¹⁹ These systems quantitatively specify, graphically organize and objectively notate colors and their relationships using standardized attributes that are based upon color appearance.²²⁰ The three most commonly utilized color order systems are the *Munsell Color System* used by painters, geologists and industry; the *Pantone Matching System*[®] (PMS) used in printing and the fashion industry; and the *Natural Color System* (NCS) used in paint manufacturing, architecture and interior design.²²¹

Munsell Color System

At the beginning of the twentieth century, drawing on the works of key nineteenth-century theorists, artist and educator Albert Henry Munsell (1858-1918) developed a three-dimensional color model for art and commerce. Munsell’s system is one of the most popular color systems in use today.²²² His 1921 *Grammar of Color* defined nine principles of color balance based upon their relationship to middle gray.²²³ The Munsell Color System is perceptually uniform and accurately and quantitatively describes color with independently functioning color variables.²²⁴ It is comprised of a theoretical system (or perceptual color

Optical Society of America, “About OSA” accessed May 1, 2016, http://www.osa.org/en-us/about_osa; and Pantone, LLC, “About Pantone,” 2016, accessed June 20, 2016, <http://www.pantone.com/about-us?from=topNav>.

²¹⁹ János Schanda, ed., *Colorimetry: Understanding the CIE System* (Hoboken, NJ: John Wiley & Sons, 2007); and Sally Cochrane, “The Munsell Color System: A Scientific Compromise from the World of Art, Part A,” *Studies in History and Philosophy of Science*, 47 (2014): 26–41.

²²⁰ Mark D. Fairchild, *Color Appearance Models* (West Sussex: John Wiley & Sons, 2013).

²²¹ Jeanne Kopacz, *Color in Three-Dimensional Design* (New York: McGraw Hill, 2004); and Verner Panton et al., *Verner Panton* (Basel, Switzerland: Basler Zeitung, 1998).

²²² Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004); and Linda Holtzschue, *Understanding Color: an Introduction for Designers* (New York: John Wiley & Sons, 2012).

²²³ Jose Luis Caivano, “Color and Semiotics: A Two-way Street,” *Color Research & Application* 23, no. 6 (1998): 390–401.

²²⁴ Sally Cochrane, “The Munsell Color System: A Scientific Compromise from the World of Art, Part A,” *Studies in History and Philosophy of Science*, 47 (2014): 26–41.

space) and color charts called atlases.²²⁵ The Munsell system is widely used by designers, artists and manufacturers to specify the colors of materials, pigments and finishes.²²⁶ Munsell offers systems for communicating color in science (i.e. for rock, soil and plant samples), the Munsell Books of Color, color management tools, software, color education and color standards for government and industry.²²⁷

Pantone Matching System

Former pre-medical student and entrepreneur Lawrence Herbert transformed a small print shop in New Jersey into a major color authority by creating uniform standards for color printing.²²⁸ In 1963, Herbert introduced the Pantone Matching System (PMS), which is based in the Munsell Color System and has become the standard for color matching in print, marketing and branding.²²⁹ Pantone offers solutions to address the problem of color inconsistency in the print and design industries.²³⁰ Through cooperative projects and licensing agreements with major software and computer companies Pantone embraced the digital era and by 2001 was the leading competitor in color management solutions.²³¹ Pantone offers a range of color products including Pantone Color Charts, color swatches, color software, color consulting, color trend forecasts, color management tools and color measurement and matching devices.²³²

²²⁵ Sally Cochrane, "The Munsell Color System: A Scientific Compromise from the World of Art, Part A," *Studies in History and Philosophy of Science*, 47 (2014): 26–41.

²²⁶ Tom Fraser and Adam Banks, *Designer's Color Manual: The Complete Guide to Color Theory and Application* (San Francisco: Chronicle Books, 2004).

²²⁷ Munsell Color, X-Rite, Inc., accessed May 15, 2016, <http://munsell.com>.

²²⁸ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge & London: MIT Press, 2012).

²²⁹ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge & London: MIT Press, 2012); and Eddie Opara and John Cantwell, *Best Practices for Graphic Designers, Color Works: Right Ways of Applying Color in Branding, Wayfinding, Information Design, Digital Environments and Pretty Much Everywhere Else* (Beverly, MA: Rockport Publishers, 2014).

²³⁰ Regina Lee Blaszczyk, *The Color Revolution* (Cambridge & London: MIT Press, 2012).

²³¹ Ibid.

²³² Pantone, LLC, "Graphics," 2016, accessed April 10, 2016, <http://www.pantone.com/graphics>.

The Natural Color System

The *Natural Color System (NCS)* has been the Swedish standard since 1979 and is centered upon Ewald Hering's *The Natural Order System of Colors* (1874).²³³ The system is based in color appearance and defines the relationship between NCS notations, the NCS Color Atlas and measurements of CIE tristimulus values.²³⁴ Colors are organized by qualitative perceptual attributes: whiteness, blackness (s), yellowness (y), redness (r), blueness (b) and greenness (g).²³⁵ The NCS system represents these psychophysical color relationships with two computer programs.²³⁶ One determines the CIE coordinates that a color material should have under specified viewing conditions for a given NCS notation and a second program measures the NCS notations of a given sample.²³⁷ NCS offers color swatches, a color reader, web applications, color training, color trend forecasts and educational materials.

Munsell, NCS, and other color order systems such as AkzoNobel, DuPont, Dulux, Toyo and RAL are systematically arranged based on perceptual attributes.²³⁸ Other notable color systems include Colorcurve, the Optical Society of America (OSA) Uniform Color Scales, the Deutsches Institut für Normung (DIN) system, and the Ostwald system. Each is prevalent relative to specific geographic regions and design

²³³ Anders Hård, Lars Sivik and Gunnar Tonnquist, "NCS, Natural Color System—from Concept to Research and Applications, Part I," *Color Research & Application* 21, no. 3 (1996): 180–205.

²³⁴ Anders Hård, Lars Sivik and Gunnar Tonnquist, "NCS, Natural Color System—from Concept to Research and Applications, Part I," *Color Research & Application*, 21 no. 3 (1996): 180–205; and Mark D. Fairchild, *Color Appearance Models* (West Sussex: John Wiley & Sons, 2013).

²³⁵ Anders Hård, Lars Sivik and Gunnar Tonnquist, "NCS, Natural Color System—from Concept to Research and Applications, Part I," *Color Research & Application*, 21 no. 3 (1996): 180–205.

²³⁶ Ibid.

²³⁷ Ibid.

²³⁸ Eddie Opara and John Cantwell, *Best Practices for Graphic Designers, Color Works: Right Ways of Applying Color in Branding, Wayfinding, Information Design, Digital Environments and Pretty Much Everywhere Else* (Beverly, MA: Rockport Publishers, 2014).

disciplines.²³⁹ The Pantone Matching System is nonetheless the most widely used system worldwide and across design disciplines, in part because the color samples are easy to access and the Pantone system costs relatively less than Munsell and NCS.²⁴⁰

10. Color Tools

There are a wide variety of color tools and apps available to advance color learning and manage color in practice. A curated list of those that are notable at this time follows. The X-Rite ColorChecker is a color calibration target that helps users replicate color under various lighting conditions and when using different cameras. It utilizes Munsell notations for 24 color swatches and has become a standard tool for modern day color accuracy.²⁴¹ Mac has a built-in application called DigitalColor Meter, which provides the RGB and hexadecimal values of any color the user selects on screen.²⁴²

Online Tools

There are many color resources available online, the following are those I found most relevant to this inquiry.

- *Adobe Color* (formerly Adobe Kuler) is a tool used by designers to find, create and save color palettes. It has been free online since 2006 and has thousands of active users.²⁴³

²³⁹ Eddie Opara and John Cantwell, *Best Practices for Graphic Designers, Color Works: Right Ways of Applying Color in Branding, Wayfinding, Information Design, Digital Environments and Pretty Much Everywhere Else* (Beverly, MA: Rockport Publishers, 2014).

²⁴⁰ Ming Ronnier Luo, "Applying Colour Science in Colour Design," *Optics & Laser Technology* 38, no. 4 (2006): 392–398.

²⁴¹ Munsell Color, "Solving Color Reproduction Issues in Photography, Printing & Television for 40 Years" X-Rite, Inc., accessed April 24, 2016, <http://munsell.com/color-blog/color-reproduction-photography-printing-television-40-years-colorchecker>.

²⁴² David Pogue, *OS X El Capitan: the Missing Manual* (Beijing & Sebastopol, CA: O'Reilly, 2015).

²⁴³ Dan Rose, *Responsive Web Design with Adobe Photoshop* (San Francisco: Adobe Press, 2015).

- *Lynda.com* has a number of color-focused tutorials including Adobe Color Essential Training and Color Management Fundamentals.²⁴⁴
- Google's *Material Design* defines a basic visual language for applying the classic principles of design. The Color section provides an overview of suggested best practices for color on the web including color swatches, color palettes, and downloadable pre-defined color themes.²⁴⁵
- *HTML Color Picker* (W3Schools) is a compact tool for designers to choose HTML colors and obtain hex and RGB values.
- *Paletton, The Color Scheme Designer* helps designers create color combinations and color palettes and offers visualization options for low saturation, color blindness simulation and two gamma corrections.²⁴⁶
- *Academo* has a great wavelength (nanometers) to RGB tool, which also provides hex values for the approximate hue of a given wavelength.²⁴⁷
- *Cambridge in Color* has a number of online tools and resources for photographers that are also valuable for designers.²⁴⁸

Color Apps

There are a variety of color apps available for smartphones that teach users about color theory and the use of color in design.

²⁴⁴ Lynda.com, "Lynda.com: Online Video Tutorials & Training," *Lynda.com, Inc.*, accessed June 24, 2016, <http://www.lynda.com>.

²⁴⁵ Google.com, "Style: Color," *Material.google.com*, accessed June 30th, 2016, <https://material.google.com/style/color.html>.

²⁴⁶ Petr Staníček, "Paletton (a.k.a. Color Scheme Designer 4)," *Paletton.com*, 2014, accessed May 1, 2016, <http://paletton.com>.

²⁴⁷ Academo, "Wavelength to Colour Relationship," *Academo.org*, accessed April 24, 2016, <https://academo.org/demos/wavelength-to-colour-relationship>.

²⁴⁸ Sean McHugh, *Cambridge in Color: A Learning Community for Photographers*, 2016, accessed April 10, 2016, <http://www.cambridgeincolour.com>.

- *Adobe Capture CC* allows designers to collect color samples with a smart phone camera and converts them into color assets easily applied in Adobe Suite software.²⁴⁹
- The *myPANTONE™* app provides Pantone color specifications, color inspiration and color palettes that are easily saved and shared.²⁵⁰
- *Color Analysis* app converts data from your camera into color profiles that include CMYK, RGB, and CIELAB to H°/C* (RGB, Hue, Chroma and hex).
- *The Interaction of Color by Josef Albers* app was developed by Yale University and won awards for the Best Interactive Product and the Spark Award for Best App in 2013.
- Other popular color apps include *Blendoku*, *Color Uncovered* and *Afterlight*.

Color Readers

Color readers are based in colorimetry. They help designers measure and match the colors of various surfaces in relation to a specific color system and provide color conversion values such as CMYK and RGB.²⁵¹ New subscription-based commercial models have emerged which are constructed around digital color readers, for example, NCS Colourpin® is a digital color reader that can be connected to a mobile device and operated through an app to digitally organize and save color samples.²⁵² Pantone CAPSURE™ is preloaded with over 10,000 Pantone colors and provides instant color matching from any surface.²⁵³ Other digital color readers include Solvita and CUBE.

²⁴⁹ Adobe, "Adobe Capture CC," Adobe Systems, Inc., accessed May 15, 2016, <http://www.adobe.com/products/capture.html>.

²⁵⁰ Pantone, LLC, "myPANTONE for Android Devices," 2016, accessed April 20, 2016, <https://www.pantone.com/mypantone-color-app-android>.

²⁵¹ Liliana Becerra, *CMF Design: The Fundamental Principles of Colour, Material and Finish Design* (Amsterdam: Frame Publishers, 2016).

²⁵² Ibid.

²⁵³ Pantone, LLC, "Pantone CAPSURE,™" 2016, accessed April 24, 2016, <http://www.pantone.com/capsure>.

CONCLUSION

The use of color in design practice is constantly evolving. The use of color has changed dramatically with the advent of contemporary color tools, color systems and color materials. Increased access to comprehensive color education will allow designers to gain mastery of a full range of technical and theoretical color knowledge. Ideally, aspiring designers would be taught the most current color production technologies in the context of the history and science of color.

Research questions for future investigations include the following: How might design students more efficiently learn color fundamentals and current technologies through avenues that are enjoyable, pragmatic, challenging and effective? How might we organize, integrate and communicate historical color theory and the contemporary technical use of color in design practice? How might we develop ways to catalog, understand and communicate color studies to designers and design student through a contemporary format other than textbooks? How might the problems of color in design be explored through design research and designed objects? Changing technology and contemporary innovations in practice might be communicated through a joint academic and trade journal dedicated to contemporary color in design practice across disciplines.

It is certain that learning and maintaining the technical skills required for the effective use of color should be a primary goal of design students, educators and professionals alike. Encouraging designers to partake in multidisciplinary courses that include topics like optics, physics of light, photography, print production and digital color is a way to utilize existing structures for increasing color knowledge. By expanding our theoretical, practical and educational understanding of color, we can improve our practices and achieve more successful outcomes in diverse design applications.

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